Keck Adaptive Optics Note 636

Next Generation Adaptive Optics
Observing Operations Concept Document

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1 Introduction

As defined in the W. M. Keck Observatory instrument development program, the Observing Operations Concept Document (OOCD) is written during the second design phase for a new instrument (i.e., the preliminary design phase). It is the third major design document written for a new instrument and follows the creation of the System Requirements Document (SRD) and the System Design Manual (SDM), both of which were written during the system design phase. The science portion of the SRD is drawn directly from the Science Case Requirements Document (SCRD).

2 Scope and Applicability

The OOCD describes how the features and functions of the design will be used to carry out the observations described in the science cases.

This document will not cover calibration of the AO system. This will be covered in a separate AO calibration document.

This document will not cover NGAO configurations (these are currently represented in KAON 550). These will be included in a separate Sequencers definition document.

3 Related Documents

This section lists the documents that are keys to developing the example observations:

- KAON 455 (SCRD): In the following sections, the references to the KAON 455 requirements are noted in italics. For example, *reqt #1.2* refers to the science case requirement #1.2 found in the KAON 455 tabulated requirements.
- KAON 548 presents a summary for the science requirements in support of the architecture evaluations.
- KAON 456 (SRD): The requirements for the science operations are described in KAON 456 under two sections: Sec. 6.1.4 for Science Operations Requirements from the Science Cases and Sec. 6.2.5 for the Observatory Operational Requirements.
- KAON 511: the System Design Manual presents an overview of the system design (AO system, laser facility, controls hardware and software, science operations and science instruments), performance budgets and requirements flow down. The detailed requirements can be found in the requirements database which is summarized in the Functional Requirements Document (KAON 573). Many of the items in KAON 511 and 573 are outdated based on the build-to-cost design changes that are summarized in KAON 642. A draft version of the preliminary design manual has been prepared which will replace KAON 511.

In addition, we have made some assumptions in developing the example observations, based on the lessons learned for LGS operations at Keck (KAON 463):

- the fraction of LGS science time lost to weather is 25%
- only 55% of the nights year-round are considered fully photometric
- the software architecture will allow for parallel operations of subsystems, reducing the overall overhead.

4 Revision History

Author	Revision Date	Version	Remarks
D. Le Mignant	June 4, 2008	0	Initial outline based on TMT and GPI OCD
F. Marchis, E. McGrath, P. Wizinowich, A. Bouchez, W. Clarkson, D. Le Mignant	Aug. 17, 2009	1.0	Release of version 1.
J. Lyke, P. Wizinowich	February 23, 2010	1.1	Minor changes & cleanup

5 Background

5.1 Top-level Requirements and Assumptions

The top level requirements that feed into the OOCD from both the science and observatory perspectives come from the SRD. This document should define an observing operations conceptual design that meets these requirements in a manner that maximizes the scientific productivity. The design process should take into account the development and operations costs associated with the conceptual design choices.

Some additional assumptions have been made by the NGAO project as a result of the build-to-cost guidelines provided by Observatory management. For the purpose of this document the following instrument assumptions have been made (these assumptions will be refined during the preliminary design):

- A near-IR imager will be provided as part of the NGAO project. This imager will extend into the visible to reach at least the Calcium triplet at ~ 850 nm.
- A near-IR integral field unit (IFU) will be provided. This IFU will extend to at least ~ 850 nm.
- OSIRIS will not be supported.
- No near-IR multi-channel deployable integral field spectrograph (d-IFS) will be provided as part of the NGAO project.
- The interferometer will need to be supported.
- The science instruments are on-axis and are located after the narrow field relay.
- No low spectral resolution capability (R ~ 1000) is currently planned but this may need to be reconsidered.

In addition the following changes have been made to the design which might impact the OOCD:

- The total laser power has been reduced from 100W to 75W, and the laser(s) will be located on the elevation moving part of the telescope.
- The total number of laser beacons has been reduced from nine to seven and the central four of these beacons will be fixed. 50W of the available laser power will be assigned to the central four beacons and 25W to the outer three beacons.
- Only one (not 3) LGS wavefront sensor lenslet arrays will be available.
- Only two (not 3) NGS wavefront sensor lenslet arrays will be available.
- The truth wavefront sensor (TWFS) previously located with the natural guide star (NGS) wavefront sensor will not be provided. The TWFS located with a low order wavefront sensor (LOWFS) will be a visible (not a NIR) detector.
- No ADC will be provided for the NGS wavefront sensor.
- No time domain or special queue scheduling will be supported. A classical observing model, similar to that currently used by Keck, is currently assumed. The TACs may choose to assign multiple programs to the same observing night as long as they provide the observer(s) to carry out these programs.

5.2 Science Instrument Basic Characteristics

The science passbands are defined in KAON 554 and the science detectors are defined in KAON 556.

5.3 Criteria for Observing Operations Success

5.4 Science Performance Simulation Tools

The following tools have been developed to support understanding and optimization of the science performance. These are in addition to the wavefront error / ensquared energy budget tool.

5.4.1 Observing Efficiency Budget

A simple MS excel-based tool has been developed to estimate the observing efficiency for the NGAO science cases. Each science case has its own spreadsheet where open shutter time and overhead have been estimated for the science target and the calibration standard. The following assumptions have been made:

- Open shutter time on the sky-calibration (telluric and flux standards, sky background) is considered science time.
- The main contributors to the observing overhead will be the telescope slews, telescope pointing adjustment and field registration, NGAO and science field acquisitions, fine centering and re-centering, and dither/offset + instrument setup + readout.
- For each contribution (open shutter and every overhead), we estimate the minimum, median and maximum values and calculate a weighted average with the following weights (1/6, 4/6, 1/6).
- Estimates for the overhead contributions from telescope slews, pointing adjustments and NGS acquisitions are derived from KAON 567.
- Additional overhead has been included for LTCS interrupts in form of an integer number of individual science integration (hence a higher impact for long integration) and subsequent time for re-centering the science target(s). Note that LTCS interrupts will be greatly reduced by the use of the “first-on-target” rule and the use of planning tools to avoid science observing during planned interrupt requests from the Laser Clearinghouse.
- The overhead for dither/offset will be reduced compared to the current system if we adopt a different strategy for dither/offset (KAON 558).
- No time loss has been included for NGAO system failure at this point as we know very little about the NGAO failure rate. This could be considered overly optimistic, yet it is counterbalanced by the allocation of maximum values for every overhead.

		Time (min)					
		min	med	max	(min+4* med+max)/6	Total	
Galaxy Field 1	Telescope slew	1	3	6	3.17		
	Adjust pointing	0.5	1	2	1.08		
	NGS acquisition	0.5	1	4	1.42		
	NGAO acq	2	4	6	4.00		
	Fine centering	1	2	4	2.17	11.83	
	Ind. Science integration	15	20	30	20.83		
	Total Science Integration	90	150	240	155.00	155.00	
	repeat	6	7.5	8	7.44		
	Dither/setup/readout	0.25	0.75	2	0.88		
		1.5	5.625	16	6.51	6.51	
Telluric calibration 1	Telescope slew	0.25	0.5	1.5	0.63		
	Adjust pointing	0	0	0	0.00		
	NGS acquisition	0.5	1	2	1.08		
	NGAO acq	1	2	3	2.00		
	Fine centering	0	0	0	0.00	3.71	
	Ind. Science integration	1	2	3	2.00		
	Total Science Integration	2	4	8	4.33	4.33	
	repeat	2	2	2.67	2.17		
	Dither/setup/readout	0.25	0.5	1.00	0.54		
		0.5	1	2.67	1.17	1.17	
Total field #1	**Total Observing**					**182.56**	
	Total Open Shutter					**159.33**	**0.87**
Flux standard	Open shutter				4.33		
(eq. to telluric std)	overhead				1.17	5.51	
	repeat per night					2	
Available hours/night		9.1	10.25	11.3	10.23		
		546	615	678	614.00		
Number of field/night					3.30		
Efficiency	**Total Observing**					**614.00**	
	Total Open Shutter					**534.94**	
	Total overhead					**79.06**	**614.00**
	Observing efficiency					**0.87**	

Figure 1: Example of an observing efficiency budget sheet

The Observing Efficiency Tool can be downloaded from:
http://www.oir.caltech.edu/twiki_oir/bin/view/Keck/NGAO/NGAOObservingScenarios

5.4.2 Telescope Slew Time Estimator

A slew time estimator is needed to optimize the observing schedule, anticipate any LGS window constraints, and improve the efficiency of the instrument on-sky by setting up the next observation configuration during slewing. At present, this tool is not yet available however slew times can be estimated from the theoretical data in Table 1 and Figure 2.

Telescope/Axis	**Max Slew** Speed (deg/s)	**Acceleration** (deg/s/s)	**Acceleration Time** to reach Slew Speed (s)	**Acceleration Distance** to reach Slew Speed (deg)	**Slew time for** **D≤2d$_\alpha$** (s)	**Slew time for** **D>2d$_\alpha$** (s)
	ω	α	t_α	d_α	$2\sqrt{D/\alpha}$	$2t_\alpha + \left(\frac{D-2d_\alpha}{\omega}\right)$
Keck 1 Az	1.0	0.05	20	10	$2\sqrt{D/0.05}$	$40+(D-20)$
Keck 1 El	1.0	0.05	20	10	$2\sqrt{D/0.05}$	$40+(D-20)$
Keck 2 Az	1,3	0.05	26	17	$2\sqrt{D/0.05}$	$52+(D-34)/1.3$
Keck 2 El	1.0	0.05	20	10	$2\sqrt{D/0.05}$	$40+(D-20)$

Table 1 Slew speeds, accelerations and times for each Keck axis above EL = 2 degrees (D = distance of move). These are ideal equations, derived from the standard equations of motion assuming constant acceleration for positive and negative acceleration periods. The telescope will not reach maximum slew speed for distances less than twice the acceleration distance.

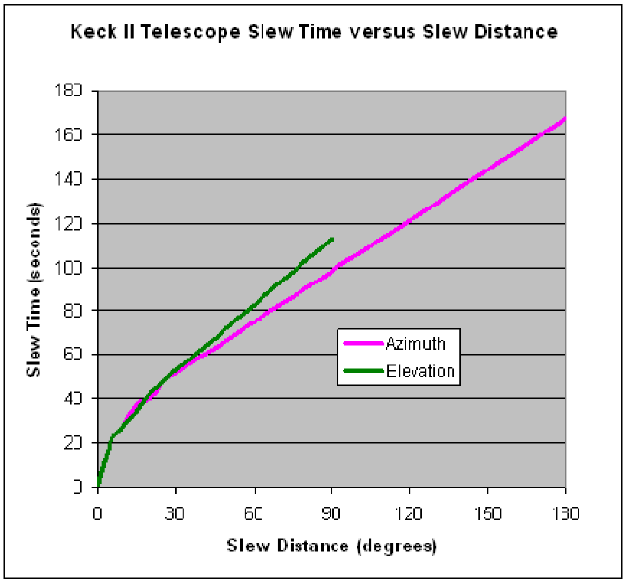

Figure 2 Keck II telescope slew time versus slew distance for elevations above 2 degrees. For slews greater than 20 degrees in distance, an additional 3 seconds has been included to the theoretical slew times to account for the time needed to settle the telescope at the end of large slews.

5.4.3 Throughput and Emissivity Budget

This is Bouchez's tool modified by Gavel.

5.4.4 Imaging Simulation Tool

The simulation software developed to simulate imaging observations of small solar system bodies taken with the NGAO near-IR and visible instruments, is described in KAON 529.

5.4.5 IFU Sensitivity Simulation Tool

This is the simulation tool developed by D. Law et al., AJ 131, 70 (2006).

5.4.6 IFU Radial Velocity Sensitivity Simulation Tool

This tool needs to be developed.

5.4.7 Photometric and Astrometric catalogs

NGS wavefront sensor will be able to analyze the wavefront on stars as faint as m(J+H+K)~20. Preparation of the observations will require access to catalogs providing astrometric and photometric measurements for faint stars. Once NGAO is commissioned several large all-sky surveys will be operational or just coming on-line like Pan-STARRS and LSST. LSST (available in 2015) will have a coverage at Y band and claims to be able to reach a limiting magnitude of Y=22 in one visit exposure (2 x 15s). However this survey is located in the southern hemisphere so it will observe a small part of the sky accessible to the Keck telescope. Pan-STARRS' prototype telescope (PS1) located on Maui, is currently being tested. It has a coverage in Y band which should go down to Y=20. Pan-STARRS final version of four 1.8m telescopes is currently being developed and should provide the first data in 2012 with a limit in magnitude in Y band of 22.

In KAON 567 a discussion about the use of existing catalogs for the NGAO shows that no evident solution can be found. The use of a combined GSC2 catalog (1" resolution, R_{limit}=19.5, but completeness down to J=17, 25% missing stars down to J=20) merged with 2MASS catalog (2" resolution, 470 millions of sources in J,H, K with J_{limit} = 15.2) is proposed as an alternative. SDSS catalog (u,g,r,I,z multi-band with 0.1" resolution survey of 180 million targets and 95% completeness down to 20.5 in z band) must be considered as a second option since the catalog covers most of the Northern Galactic hemisphere above galactic latitude of b = 35 deg. Similar conclusions are described in Nelan (2003) for the JWST which has a fine guider sensor sensitive up to J~20.

At the end of 2009, the NASA-Funded WISE satellite will be launched. It will conduct a one-year all-sky survey from 3 to 25 µm (4 channels) with a 2” resolution providing a catalog that includes M dwarf with J~17. This catalog could be a third alternative since it will provide a complete and accurate all-sky survey useful for the NGAO.

5.4.8 Ephemeris calculator for small solar system bodies and planets

An ephemeris calculator which provides the celestial coordinates of planets and small solar system bodies (asteroid, comets, TNOs) predicted at the time of observation is necessary during the preparation and during the night of observations (Section 6.5.1). SKYBOT (http://www.imcce.fr/page.php?nav=webservices/skybot/) is an ephemeris calculator which uses orbital elements of small solar system bodies from the ASTORB Table (439325 targets in January 2009) using DE405 planetary theory from JPL. SKYBOT is VO-compliant and can be accessed as web services. Current tests indicate that coordinates of an asteroid can be obtained in less than 50-80 ms from Keck headquarters. The server is currently located at the IMCCE of the Observatoire de Paris. SKYBOT2, which will be finalized in June 2009, will be 5-100 times faster and a mirror server will be installed in California in 2010. We may consider installing a local ephemeris calculator at Keck Observatory to improve the reliability.

5.4.9 Ephemeris calculators for satellites of Giant Planets

The satellites of the Giant (Jupiter and Saturn) and Icy Planets (Uranus and Neptune) can be used as a tip-tilt reference for the study of the planets and their environment (see science case in section 7.4). The brightness and relative position (with respect to the planet) of the satellites need to be calculated to predict the optimal period of observations and also to derive the relative positions of the satellites during the observations. The IMCCE provides ephemeris calculations for several satellites of the Giant planets (see http://www.imcce.fr/page.php?nav=fr/ephemerides/generateur/saimirror/nssephe.php). The ring Nodes (http://pds-rings.seti.org/tools/) also provides a moon tracker ephemeris for a limited number of satellites. A tool gathering the ephemeris of satellites which could be used as reference for the NGAO TT per planet is needed. It could be built to interface with these web sites or the Horizon JPL ephemeris.

6 Key Science Driver Observations

This section presents sample observations for each of the five Key Science Drivers described in the SCRD (KAON 455).

6.1 Galaxy Assembly and Star Formation History

The requirements for the galaxy assembly and star formation history science case are described in section 2.1 of the SCRD. The system design version of the SCRD assumed the existence of a d-IFS. This section has been written assuming that only a single near-IR IFU will be available.

6.1.1 NIR Imager Observations

6.1.1.1 Description

Imaging goals for this science case are to obtain high-spatial resolution information of star forming regions as well as overall galaxy morphology, bulge-to-disk ratios, and merger morphologies in order to learn about the processes driving galaxy formation and evolution during the key era of star formation and galaxy assembly, 2.5 < z < 1.5. Observations on both the short and long sides of the 4000 Å-break will allow comparisons between the morphologies imprinted on the galaxy at early times against those due to recent star formation. At a redshift of z=1.5, the 4000 Å-break is redshifted to 1 micron (i.e., J-band), while at z=2.5 it is redshifted to 1.4 microns (i.e., H-band). Observations in z – K-band will therefore be a key for this science case.

Parameters	Value / Method	Comments
Science instrument	NIR Imager	
Instrument setup	FoV ≥ 10 arcsec z-K wavelength range 13 mas pixels, Nyquist at J-band	Will want a K′ or similar filter that excludes the thermal part of K-band. Can recover some spatial information at shorter λ through sub-pixel dithering.
Total integration time on target	1 - 2 hours	
Individual integration time on target	30s x 4 co-adds in K-band	

Individual integration time on calibration stars	5 - 20 sec in K-band	
Positioning precision of imager with respect to the NGS	< 70 milli-arcsec (KAON 548)	
Positioning knowledge of imager	< 5mas (KAON 540) λ/10D in K-band	
Background estimation	Dither on instrument	
Instrumental calibration	Dome flats, darks	Performed during the day
PSF calibration	Using a PSF star in the field or dedicated observing sequence	Telemetry-based PSF reconstruction
Photometric calibration standard	Dedicated observing sequence	

Table 2: Summary of the NIR imager observing parameters for the "galaxy assembly and star formation history" science case

6.1.1.2 Pre-observing tasks

See Section 6.6.

6.1.1.3 Observing tasks

See Section 6.8.

6.1.1.4 Post-observing tasks

See Section 6.10.

6.1.2 NIR IFU Observations

6.1.2.1 Description

The original observing goal for this science case was to survey more than 200 galaxies over a few years (*reqt #1.2*). Without a multi-unit deployable-IFU, this will not be possible. Instead, we plan to survey a smaller selection of targets chosen to be complementary to samples observed elsewhere (e.g., JWST, VLT). Depending on the object brightness, the NGAO + IFU will dedicate ~ 1.5 to 4 hours of open shutter time on a target (*reqt #1.2*). Typical values for integrated galaxy magnitudes are m_{Vega}~20.5 in K-band, and typical integrated line fluxes are ~few x 10^{-17} erg s^{-1} cm^{-2}.

Parameters	Value / Method	Comments
Science instrument	NIR IFU	
Instrument setup	IFU FoV: 1 x 3 arcsec J-K wavelength range 70 mas/spaxel 35 mas/pixel TBD	
Total integration time on target	1.5 - 4 hours	*reqt #1.2*
Individual integration time on target	15 - 30 min	
Individual integration time on calibration stars	20 - 60 sec	
Positioning precision of IFU with respect to the NGS	< 70 milli-arcsec (KAON540)	Goal of 70 milli-arcsec (TBD) between LOWFS arms and IFU?
Positioning knowledge of IFU	< 5mas (KAON 540) λ/10D in K-band	
Background estimation	Dither on IFU	Observers are likely to use a dithering script on the IFU
	Dedicated background by offsetting to a blank field once every ~15 min.	M. Perrin's scaled sky subtraction module (based on method in Davies 2007) could

		help reduce frequency of required sky frames.
Instrumental calibration	Using arc lamps and integrating sphere	Performed during the day
PSF calibration	Using an on-axis imager? Dedicated observing sequence	Telemetry-based PSF reconstruction
Telluric standard	Dedicated observing sequence	

Table 3: Summary of the IFU observing parameters for the "galaxy assembly and star formation history" science case

6.1.2.2 Assumptions and pre-requisites

In estimating the observing efficiency, we have made the following assumptions:

- Because we will not have a multi-unit deployable-IFU, we cannot produce a 3-D PSF for calibration by using an IFU to monitor a PSF star in parallel with the observations. We therefore assume that a dedicated PSF star observation may be required at regular intervals throughout the observation. These will generally be short exposures and will add approximately 5 min (?) per PSF star observation to the total observing time. Alternatively, it may be possible to monitor an off-axis PSF with a NIR imager and use tomographic reconstruction to determine the shape of the PSF on-axis.
- For every set of targets, we anticipate the observer will calibrate for the telluric absorption after the science spectroscopy observations and within a certain interval in air mass and time. This should add approximately 10 min of observing time to the observations of the set of targets. In addition, we anticipate the observer will want to calibrate the flux by observing flux standards, twice through the night, and possibly including during twilight.
- We assumed individual integration time between 15 and 30 min on the NIR IFU for the science targets and between 1 and 3 min for the standards.
- For an observation of a target, we find that it will take 12 min on average for the full setup from initiating the telescope slew until first start of science-quality exposures. The open shutter time will be 155 min on average with 3 min of overheads for dither/readout and 5.3 min for re-centering. The observation of the telluric of flux standard will take approximately 9 min including ~ 55% total overhead (telescope slew, acquisition, dither, readouts).
- We anticipate 27 min loss due to LTCS interrupts, mainly a consequence of the long integration times.

Using these assumptions, we derive that it will be possible to observe 3.14 science fields including the telluric standards and two flux standards for an average night of 10.25 hours numbers.
The total observing efficiency (open shutter on science, including standards) is 83%.

Assuming 1science target in the IFU field of view, this leads to 3 observed targets per full observing night.

6.1.2.3 Observing model

The PI astronomer and her/his team would need ~ 20 full observing nights to collect data for ~ 60 objects. Assuming a weather-loss fraction of 0.25 (KAON 463), this requires ~ 27 allocated nights (spread over a few semesters) to collect the needed sample of data.

Astronomers are requesting half to full night(s) for this science case in classical observing mode. The astronomer(s) will be performing the observations remotely (either from Keck headquarters or elsewhere) and assessing the data quality on-the-fly. The observations require less than 1 mag of extinction in the V band (for the use of lasers). The PI and the science team are responsible for the backup observing program.

The science instrument configuration will be detailed during the Detailed Design phase for NGAO in parallel to the studies for the NIR IFU. KAONs 455 and 548 provide details for the NIR IFU (previously d-IFS): a spaxel size of 70 milli-arcsec (2 pixels of 35 mas/spaxel) and a field-of-view of ~ 1.0 x 3.0 arcseconds (*#reqt 1.8*).

6.1.2.4 Pre-observing tasks

See Section 6.7.

6.1.2.5 Observing tasks

See Section 6.9.

6.1.2.6 Post-observing tasks

See Section 6.10.

6.2 Nearby Active Galactic Nuclei

The requirements for the nearby active galactic nuclei (AGN) science case are described in section 2.2 of the SCRD.

6.2.1 NIR Imager Observations

6.2.2 NIR IFU Observations

6.2.2.1 Description

This science case will target a number (< 25?) of nearby AGN that have independent black hole (BH) mass measurements from other methods (reverberation mapping, etc.) in order to calibrate the M_{BH}-σ relation, as well as new targets (< 100 ?) that will extend the M_{BH}-σ relation to lower BH masses and greater distances. Crucial to this science case is the ability to resolve the sphere of influence of the central black hole so that accurate BH mass measurements can be made (and are not contaminated by the surrounding stellar mass). If the IFU wavelength range extends to 850 nm, this will yield more targets at greater distances. The central AGN cannot be used as a TT reference "star". Treatment of the background light from the galaxy will provide unique challenges for the WFS. Three TT reference stars may not be available for all targets due to the extent/ brightness of the host galaxy. Depending on whether stellar or gas dynamics are used for kinematics, NGAO + IFU will dedicate ~ 1 to 3 hours of open shutter time on a target.

Parameters	Value / Method	Comments
Science instrument	NIR IFU	
Instrument setup	IFU FoV: 1 x 3 arcsec z-K wavelength range (850 – 2400 nm) 20 mas/spaxel 10 mas/pixel TBD	Narrow band filters targeting specific spectral features (e.g., Ca II triplet, Br gamma, etc.) radius of influence of BH: $\sim 20\ (M_{BH}/10^6 M_\odot)^{0.5}$ / (D/10 Mpc) mas
Total integration time on target	1 - 3 hours	longer observations for stellar dynamics?
Individual integration time on target	10 - 15 min	Do not saturate the central AGN point source
Individual integration time on calibration stars	20 - 60 sec	
Positioning precision of IFU with respect to the NGS	< 100 milli-arcsec	goal of 20 milli-arcsec? between LOWFS arms and IFU?
Background estimation	Dedicated background by offsetting to a blank field once every ~10-20 min.	See also, M. Perrin's scaled sky subtraction module and Davies (2007)
Instrumental calibration	Using arc lamps and integrating sphere	Performed during the day
PSF calibration	Dedicated observing sequence Using spatially unresolved spectral features?	
Telluric standard	Dedicated observing sequence	

Table 4: Summary of the observing parameters for the "nearby active galactic nuclei" science case

Ref: Davies, R. I. 2007, MNRAS, 375, 1099

6.2.2.2 Assumptions and pre-requisites

In estimating the observing efficiency, we have made the following assumptions:

- Because we will not have a multi-unit deployable-IFU, a PSF star cannot be observed in parallel with the observations for calibration purposes. We therefore assume that a dedicated PSF star observation may be required at regular intervals throughout the observation. These will generally be short exposures and will add approximately 5 min (?) per PSF star observation to the total observing time.
- For every set of targets, we anticipate the observer will calibrate for the telluric absorption after the science spectroscopy observations and within a certain interval in air mass and time. This should add approximately 10 min of observing time to the observations of the set of targets. In addition, we anticipate the observer will want to calibrate the flux by observing flux standards, twice through the night, and possibly including during twilight.
- We assumed individual integration time between 10 and 15 min on the NIR IFU for the science targets and between 1 and 3 min for the standards.
- For an observation of a target, we find that it will take 12 min on average for the full setup from initiating the telescope slew till first start of science-quality exposure. The open shutter time will be 120 min on average with 3 min of overheads for dither/readout and 5.3 min for re-centering. The observation of the telluric of flux standard will take approximately 9 min including ~ 55% total overhead (telescope slew, acquisition, dither, readouts).
- We anticipate 27 min loss due to LTCS interrupts, mainly a consequence of the long integration time.

Using these assumptions, we derive that it will be possible to observe ~5 science fields including the telluric standards and two flux standards for an average night of 10.25 hours numbers. The total observing efficiency (open shutter on science, including standards) is xx%.

6.2.2.3 Observing model

The PI astronomer and her/his team would need ~20 full observing nights to collect data for ~ 100 objects. Assuming a weather-loss fraction of 0.25 (KAON 463), this requires ~25 allocated nights (spread over a few semesters) to collect the needed sample of data.

Astronomers are requesting half to full night(s) for this science case in classical observing mode. The astronomer(s) will be performing the observations remotely (either from Keck headquarters or elsewhere) and assessing the data quality on-the-fly. The observations require less than 1 mag of extinction in the V band (for the use of lasers). The PI and the science team are responsible for the backup observing program.

The science instrument configuration will be detailed during the Preliminary and Detailed Design phases for NGAO in parallel to the studies for the NIR IFU. KAONs 455 and 548 provide details for the NIR IFU: a spaxel size of 20 milli-arcsec (2 pixels of 10 mas/spaxel), a field-of-view of ~ 1.0 arcseconds (*#reqt 2.4*).

6.2.2.4 Pre-observing tasks

See Section 6.7.

6.2.2.5 Observing tasks

See Section 6.9.

6.2.2.6 Post-observing tasks

See Section 6.10.

6.3 Astrometric Measurements of General Relativity Effects in the Galactic Center

The requirements for measurements of General Relativity effects in the Galactic Center (GC) are described in section 2.3 of the SCRD. These include accurate determination of the orbits of stars orbiting Sgr A* through astrometric imaging and radial velocity measurements, both in the near-IR.

6.3.1 Near-Infrared Imaging of the Galactic Center

This science case provides the most restrictive and technologically challenging constraints on the NGAO system astrometry requirements: ≤ 100 μas for objects ≤ 5 arcsec from Sgr A* (*reqt #3a.1).*

The proposed H and K-band observations of the 10" x 10" field centered on Sgr A* aim at measuring and monitoring the orbits of the closest stars to the massive black hole at the Galactic Center. With Keck NGAO, the orbits can be monitored with sufficient precision to enable a measurement of post-Newtonian general relativistic effects associated with the black hole. The current limitations to the measurements are 1) the confusion limit because the GC is a very crowded field and 2) field distortions due to the atmospheric refraction, tilt anisoplanatism and instrument distortions.

6.3.1.1 Description

The observing goal for this science case is the H and K-band astrometry and photometry for the 10" x 10" field centered on Sgr A* located at RA 17 45 40.04 DEC -29 00 28.12. Capability in both K' and H is required. As source confusion is the dominant source of positional error in the central arcsec, at least a moderately-deep map in H-band will be required to estimate an unbiased position of SgrA* itself in each epoch.

Parameters	Value	Comments
Science instrument	NIR camera	
Instrument setup	FoV: 10 x 10 arcsec H & K wavelength < 10 mas/pixel	Nonlinear instrument distortion characterized and stable to <0.1mas. Linear distortion characterized and stable to 0.5 mas (requirement), ideally 0.1 mas (goal).
Target observability	3 hours at airmass ≤ 1.7 1 h at 1.7 ≤ airmass ≤ 2	
Individual integration time on target	ncoadds x ind. integ. time = 10x3s	3s: set by saturation – see assumptions below. 10 integrations:based on experience with existing LGSAO system: LBWFS sets minimum time at each dither position to 3 minutes. Three frames are required per dither position to estimate centroiding precision. With overheads, this leads to 30s exposures per frame.
Observing efficiency	≥ 35%	Requires reading smaller array/FoV? No – want the full fov for frame:frame transformations. Require readout overhead? Yes but perhaps not critical. Requires ND filters? No
Dynamic range	Must be capable of observing K=9 in a single integration without saturating. At least 9 < K <18 per frame.	For our assumptions below, linearity and detector well-depth allow five times the signal per integration compared to NIRC2 before significant nonlinearity sets in.
Positioning precision of Sgr A*	< 100 milli-arcsec	
Background estimation	Small random dither in a ~1 x 1 arcsec box Size of the box depends on the amplitude of the camera distortions.	Using randomly generated positions. Re-use existing random sequence for repeatability and compatibility with NIRC2 datasets. Size of dither/dithering method that will minimize overheads.
Instrumental calibration	Flat field and astrometry	Internal calibration during the

		day, validated by regular on-sky calibrations
Field registration against MASER sources	Observe a 40 arcsec x 40 arcsec mosaic to map GC and MASERs	Requirements for this registration: Linear distortion characterized and repeatable to 0.5mas (0.1mas goal).Main error terms for astrometry will be: - Pick-off arms registration - Camera(s) distortions - TT residuals
PSF calibration	From modeling the 2-D field-dependent profile based on star extraction, AO and C_n^2 telemetry.	Telemetry-based PSF reconstruction. With field-varying PSF, PSF determination may be the limiting factor in astrometric precision. Require the ability to estimate the PSF centroid to 0.1mas or better.

Table 5: Summary of the observing parameters for the "Galactic Center imaging" science case

6.3.1.2 Assumptions and pre-requisites

In estimating the observing efficiency, we have made the following assumptions:

- The field is observable for 3.5 hours during the night from Keck II.
- Confirm pixel scale/FoV requirements (based on PSF sampling but also SNR/linearity/saturation/observing efficiency)
  - From KAON 548: pixel scale is ≤ 13 mas, Nyquist sampling at J band
  - ≤ 10mas desired to sample PSF artifacts.
- Individual integration times are:
  - K': 10x3 s.
  - H: extra magnitude in extinction, but we expect some level of psf smearing for longer exposures, and longer exposures increase the total allocation requirement. We adopt 30x3s.
- The detector has greater well-depth than NIRC2 to permit similar efficiency in exposures limited by bright objects. In particular:
  - We assume the count rate in the brightest pixel scales with Strehl^2 (e.g. Hardy 1998 p. 42).
  - Strehl in K' with NIRC2 + LGS AO typically 35% or so; target NGS AO Strehl 80%.
  - Therefore the brightest pixel from the brightest star in the scene would saturate in ~20% of the time compared to NIRC2.
  - For planning purposes, we are therefore assuming that the detector linearity and well-depth allow recording of five times the signal of NIRC2 in the same time without saturation or significant nonlinearity.
- We anticipate no loss due to LTCS interrupts, assuming we will be first on target.

Strategy and division between filters: We assume that a single measurement at 0.1mas precision requires 100 good frames. Experience suggests this represents perhaps 2/3 of the frames actually taken (the rest being used for secondary science). This leads to one half-night per measurement. We operate under the assumption that the majority of frames will be taken in K' due to the shorter integration required per frame for the same signal. A subset of frames will be taken in H to estimate the position of SgrA*. Our expectation is 150 frames per half-night in K', plus 20 frames in H.

The total observing efficiency (open shutter on science, including standards) is 35% or better. We assume overheads due to readout to be roughly similar to NIRC2 experience, so that during a continuous exposure sequence, the effective integration time is approximately 50% of the sequence. 20 minutes will be required for skies in each filter, 20 for any extra darks across both filters. Anticipating 150 frames per half-night, this suggests total efficiency ~150*0.5 / 210 =36% (we round down). Daytime calibrations not included. Note that if the Strehl is increased with no increase in well-depth of the detector, then the minimum exposure time will be shorter and thus the efficiency lower. This efficiency estimate TBC when the full efficiency planning spreadsheet becomes available.

Assumptions for setting the 40"x40" mosaic requirements:

- Want error in the relative motion of IR and radio frames to be 0.1mas/yr or lower. Presently, the error in the radio for SgrA* motion against the masers is about 0.14 mas/yr (Reid et al. 2007), though we anticipate this will improve to ~0.1 mas/yr or better as more observations are taken and with more masers in the wider mosaic. This then leads to error in the relative motion of SgrA* in the radio-transformed IR frame, of <0.15 mas/yr.

- Random error due to propagation forward of radio positions is presently 1.4 mas. We assume a similar figure will obtain during the NGAO era.
- For the maser mosaic observations, a centroiding error of 1.4 mas in the NIR is conservatively adopted.
- The error in relative motion between the NIR/radio frames is then the error in the gradient of a straight line fit to the NIR – radio position differences, averaged over 9 SiO masers within the 40"x40" field of view (allowing for some quality control).
- To be conservative, we allow for 4/10 epochs to be clouded out by poor conditions, provided one of the last two epochs in the 10 year time base is still obtained.
- 0.5 mas repeatability after distortion-correction (not including NIR centroiding errors) should permit the IR:radio frames to be mapped to the required precision. 0.1 mas distortion correction is the goal, as this would support further improvements in radio and IR centroiding.
- We want absolute astrometry of the SiO masers and SgrA* itself to about 3 mas, so that the dynamic center can be determined independently of the dynamical fit, to ~1mas (averaging over 9 masers).

There are several challenges for NGAO on this field:

- High extinction towards the target, as illustrated in Figure 3. The high extinction can lead to difficulties in identifying the NIR NGS stars in the R-band images from the acquisition camera. This is a case where a set of R-band source might be needed to ID the field, then center the field on a dynamic pointing origin, such as to allow the NIR guide stars to be aligned with the LOWFS pick off.

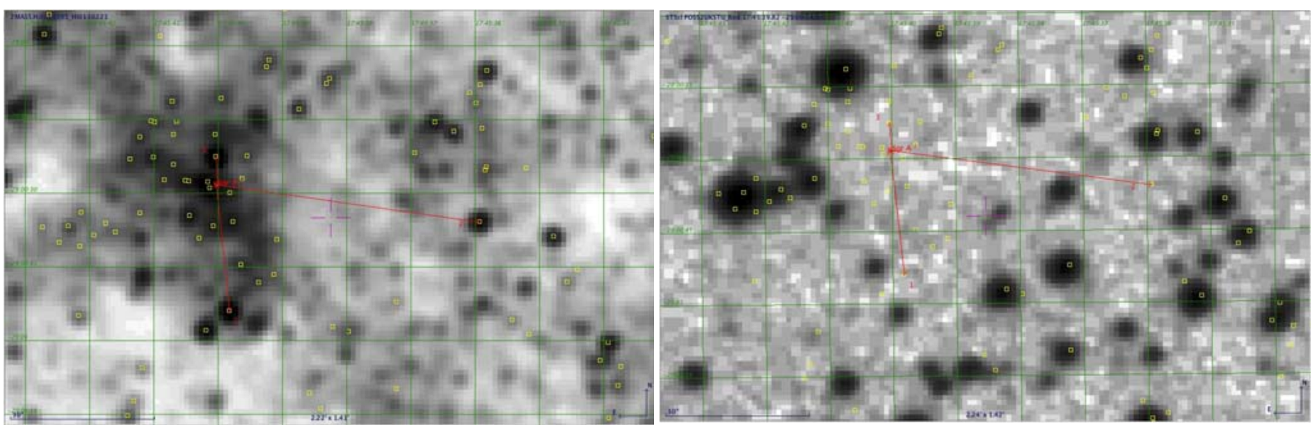

Figure 3 : Galactic Center in H (left) and R band. Yellow squares indicate stars with J, H and K < 15 mag. The field of view is ~ 85" x 130". The intersection of the 3 vectors denotes the location of Sgr A*.

- The presence of very bright stars (e.g., K~ 6.5 mag.) in the vicinity of Sgr A * constrains the NIR detector integration time and the field-of-view. In the past (NIRC2), tip-tilt star USNO-A3.0 0609-0602733 (17 45 40.710 -29 00 11.20 2000.0 rmag=14.0 sep=19.3) has been used. A random but repeatable dither pattern (within a 0.7"x0.7" box) has been generated that well samples the scene, while keeping IRS7 (at K=6.5, the brightest local object) off the 10"x10" detector at all times. The brightest objects of scientific interest in the field are at K=9; we must not saturate these objects in a single integration. In order to maximize efficiency while avoiding persistence issues, a 10"x10" subarray of the detector will likely be used for the observations of the GC itself.

- Optimal selection for the LOWFS NGS: the yellow squares indicate the stars that are brighter than magnitude 15 in J, H and K band. There are more than 50 stars in a 2 arcmin x 2 arcmin box centered on Sgr A*. The best selection will be a function of the stars brightness (bright star case without reaching saturation in the LBWFS), and the morphology of the stars geometry that will minimize the estimation error for the low-order modes. The optimum choice in terms of minimum wavefront error is a topic of future work: for now, a selection of the brightest stars ≥6 arcsec from SgrA* is presented in Table 6. We note that, depending on the arrangement of the LOWFS pick-off arms around the science field, IRS7 itself (star 4 in Table 13) may be a good choice for the northern NGS; as we keep this object off the detector at all times, vignetting of the science field by its associated pickoff arm may not occur.

#	2MASS ID	J	H	K	Distance from Sgr A* (arcsec)	Approx PA (E of N) from Sgr A* (deg)
1	17454044-2900344	14.9	10.5	8.0	8.6	153
2	17453982-2900539	13.6	9.5	7.4	24.6	187
3	17453593-2900357	14.5	10.3	8.2	54.2	262
4	17454004-2900225	14.2	9.3	6.5	6.0	0
5	17454130-2859379	14.7	10.5	8.3	51.8	17

Table 6: Example of possible very bright AO guide stars for the Galactic Center

Pointing for the 40"x40" mosaic:

- Full-field will be used to maximize efficiency; integration time of order 0.1 s per integration will be required not to saturate.
- A 3x3 dither pattern using 9" steps should allow all points in the mosaic to lie within 10" of the LGS asterism for at least one pointing. Depending on the optimization used, Figure 10 of KAON 644 indicates a performance drop of ~10-15% for stars more than ~10" from the LGS asterism.
- The LGS asterism will remain at the center of the field at all times.

6.3.1.2.1 Observing model

Ten measurements per season are necessary to observe the effect, at one half-night per measurement (see assumptions above). The PI astronomer and her/his team would need 10 half (and 0 full) observing nights each year. Assuming a weather-loss fraction of 0.25 (KAON 463), this requires 13 allocated half-nights (spread over one year) to collect the needed sample of data.

Astronomers are requesting half nights for this science case in classical observing mode. The astronomer(s) will be performing the observations remotely (either from Waimea or elsewhere) and assessing the data quality on-the-fly. The observations require less than 1 mag of extinction in the V band (for the use of lasers). The PI and the science team are responsible for the backup observing program.

The science instrument configuration will be detailed during the Preliminary and Detailed Design phases for NGAO. KAON 548 provides information for flow-through to instrument-level requirements.

6.3.1.3 Pre-observing tasks

See Section 6.6.

6.3.1.4 Observing tasks

See Section 6.8.

6.3.1.5 Post-Observing tasks

See Section 6.10.

6.3.2 Near Infrared Radial Velocity Measurements of the Galactic Center

Current IFU radial velocity measurements of stars near SgrA* have ~20 km/s precision. To allow detection of GR precession due to SgrA* on a 10-year timescale, an IFU that can deliver 10 km/s precision is required (SCRD Section 2.3.2, Figure 8). Experience with OSIRIS suggests the key limitations are: 1. SNR per spaxel (throughput limitation); and 2. Spectral resolution (many lines are blends). Secondary concerns are 3. Image quality (background estimation and source separation); and 4. DAR correction.

6.3.2.1 Description

Obtain at least ten radial velocity measurements per year of the region at least 1.5"x1.5" surrounding SgrA* (RA 17 45 40.04 DEC -29 00 28.12). K-band spectroscopy is a priority as 1. Experience with OSIRIS is most developed in this waveband and 2. the Strehl will likely be higher than H-band, allowing better background estimation. H-band capability is desired due to blends between Br-gamma (2.166 μm) and the nearby He-II (2.112 μm); e.g. Brackett 11-4 (1.68 μm) and He-I (1.70 μm) may prove superior tracers. Requirements are as follows:

Parameters	Value	Comments
Science instrument	IFU Spectrograph	
Instrument setup	FoV at least: 1.5 x 1.5 arcsec H & K wavelength 20,30 mas/spaxel at H,K	
Filters	Kn3 (2.121-2.229 μm) Kn4 (2.205-2.323 μm) Hn4 (1.677-1.760 μm)	Br-gamma (2.166 μm) CO bandhead (2.294 μm) Br-11 (1.681 μm), He-I (1.700 μm)
Target observability	3 hours at airmass ≤ 1.7 1 hours at 1.7 ≤ airmass ≤ 2	
Individual integration time on target	ncoadds x ind. integ. time = 1x900 s	Based on OSIRIS experience
Observing efficiency	70%	Expect ten frames per half-night
Positioning precision of Sgr A*	10 mas	
Background estimation	From blank sky between sources.	Drives the high strehl requirement.
Telluric calibration	A0V at similar airmass for atmospheric and instrumental features, using a G2V at similar altitude to replace Br-gamma and He-I features in the A0V spectrum.	
Instrumental calibration	Wavelength calibration and spectroscopic flatfields	Observe blank patch of sky for wavelength calibration, take arcs during the day.
PSF calibration	From modeling the 2-D field-dependent profile based on star extraction, AO and C_n^2 telemetry.	Telemetry-based PSF reconstruction

Table 7: Summary of the observing parameters for the "Galactic Center IFU" science case

6.3.2.2. Assumptions and pre-requisites

We assume the IFU will be similar in many respects to OSIRIS, so we scale our expectations from that instrument. In order to double the velocity resolution over existing OSIRIS datasets, the following improvements are required:

- Higher throughput to increase the SNR per spaxel; total SNR/spaxel should be 4x that of OSIRIS for the same source brightness.
- R~4000 is the goal spectral resolution provided the throughput per spaxel can be sufficiently increased compared to OSIRIS.
- Because of the blend between Br-gamma and He-I 2.112 μm, R~15,000 is desirable. This would improve velocity measurement precision to 1km/s and in some cases may permit GR precession detection from radial velocities alone.
- Spatial sampling requirement is driven primarily by the need to obtain sky regions. As stars separate in velocity space, spatial separation of stellar sources is a second-order requirement.
- Minimum spaxel size is set by the requirement to sample the spatial profile; once this is achieved, smaller spaxels just reduce the SNR per spaxel. Over a 15-minute integration, spatial profile-width of order 40, 60 mas might be achieved in H,K' (currently ~70-85 mas in K' with OSIRIS+LGS towards SgrA*). Adopting 2 spaxels/FWHM leads to 20,30 mas spaxels in H,K'.

Spectroscopic standard stars:

- A0V – HD195500 (K=7.20, V=7.3)
- G2V – HD193193 (K=5.76, V=7.2)

Field of regard:

- Because of significant line emission in the SgrA* environment, skies must be obtained from regions between the stars in the SgrA* field. Experience with OSIRIS suggests a 1.0"x1.0" field of view should be (just) sufficient to meet this requirement, however 1.5"x1.5" would provide greater flexibility to choose sky regions during the analysis.

- The SCRD places the measured stars in the central 1.0"x1.0" from SgrA*. Dithering of order 0.5"x0.5" will be required to defeat hot pixels and provide better PSF sampling. Observations will be maximally efficient if the full science field is sampled in every integration; this leads to at least 1.5"x1.5" field of regard.
- We thus opt for 1.5"x1.5" field of regard as the minimum requirement.

Integrations required: the SCRD calculations assume 10x15 minute exposures per measurement. Experience with OSIRIS suggests this can be obtained in a single half-night.

Observing efficiency: Experience with OSIRIS suggests 150 minutes on-source in three hours; telluric standards each take 20 minutes of which ~3 minutes is time on-source. Another 20 minutes is taken up with observing a blank sky patch for wavelength calibration, and detector flushing to remove persistence. So: total efficiency ~155/215 = 72%

6.3.2.3. Observing model

Require at least 10 measurements per year (SRD 2.3.2), each of which takes one half-night. We therefore assume 10 half-nights per year are required, or with weather allowance, 13 half-nights per year.

Astronomers are requesting half night(s) for this science case in classical observing mode. The astronomer(s) will be performing the observations remotely (either from Waimea or elsewhere) and assessing the data quality on-the-fly. The observations require less than 1 mag of atmospheric extinction in the V band (for the use of lasers). The PI and the science team are responsible for the backup observing program.

6.3.2.5. Pre-observing tasks
See Section 6.7.

6.3.2.4 Observing tasks
See Section 6.9.

6.3.2.5. Post-observing tasks
See Section 6.10. In addition, the astronomer should maintain detailed logs of the setup in order to efficiently set up subsequent runs.

6.4 Imaging and Characterization of Extrasolar Planets around Nearby Stars

The requirements for imaging and characterization of extrasolar planets around nearby stars are described in section 2.3 of the SCRD.

6.4.1 Imaging of Extrasolar Planets around Nearby Stars

6.4.1.1 Description

The observing goal for this science case is to search and characterize companions around low mass stars. Coronagraphic observations in the near-infrared (J and H-band) of close environment (<5") of three target samples (see Table 9). Spectral differential imaging (SDI) or Angular Differential Imaging (ADI) for reducing speckle effects could be used, specifically for sample 2. This science case which is a search survey requires the observation of several hundred of targets (20 per night) over three years. Careful optimization of the efficiency of the observations (including centering of coronagraph and ADI/SDI) is needed.

Table 8: Summary of the observing parameters for the “Imaging and Characterizing Extrasolar Planets around Nearby Stars” science case

Parameters	Value	Comments
Science instrument	NIR camera + SDI (ref 1) or ADI (ref 2s)	low R IFU may be considered
Instrument setup	FoV: 5 x 5 arcsec J & H wavelength 11 mas/pixel	require Nyquist-sampled data for SDI or ADI
Target observability	At least 30 min at airmass ≤ 1.6	
Individual integration time on target	ncoadds x ind. integ. time = 2-5 min	Evaluate linearity and saturation time?

Observing efficiency	good peak SNR (>1000) in less than 30 min including 20 min integration time on target	Requires reading smaller array/FoV: 3" Require readout overhead? Requires ND filters: NO
Positioning precision of target	At least 5 mas (Table 9, see 4.10)	
Background estimation	Background estimated by offsetting the telescope.	Offset should be larger than FOV to avoid saturation of detector
Instrumental calibration	Flat field and astrometry	Internal calibration during the day, validated by regular on-sky calibrations
PSF calibration	From modeling the 2-D field-dependent profile based on star extraction, AO and C_n^2 telemetry.	Telemetry-based PSF reconstruction
Field identification	Using Guiding camera after comparison with known star catalog	Data saved in WCS format
Instrumental calibration	Flat field and astrometry	Internal calibration during the day, validated by regular on-sky calibrations

ref 1: Lafreniere et al, ApJ 661L1208-1217, 2007

ref 2: Marois et al, ApJ 641:556-564, 2006

6.4.1.2 Assumptions and pre-requisites

To calculate the observing efficiency, we have made the following assumptions

- Total Exposure time ranging from up to 20 min for target with H magnitude ranging 13-14 and R magnitude from 17 to 19
- pixel scale is not yet defined by simulation. λ/2D in J is mentioned in SCRD (11 mas in J band). Nyquist sampling is needed for efficient SDI or ADI [Macintosh Personal confirmation]
- Targets is observed at airmass <1.6
- Angular separation between two targets is less than 10 degrees in average limiting the time lost due to slewing the telescope

6.4.1.3 Observing model

The PI and its team will need 3 nights per year over 3 year to complete this program per sample. Assuming a weather-loss fraction of 0.25 and at least 30 min per target including exposure time (less than 20 min) + overhead, several hundred of targets will be observed.

Astronomers are requesting half to full nights for this science case in classical observing mode. The astronomers will be performing the observations remotely (either at Waimea or elsewhere). The PI and the science team are responsible for the backup observing program.

6.4.1.4 Pre-observing tasks

See Section 6.6.

6.4.1.5 Observing tasks

See Section 6.8.

6.4.1.6 Post-observing tasks

See Section 6.10.

6.5 Multiplicity of Minor Planets

The requirements for the multiplicity of minor planets science case are described in section 2.5 of the SCRD. This science case includes two programs: a search for asteroid companions and a characterization of the mutual orbits of known multiple systems in direct imaging using the visible or near-infrared cameras.

6.5.1 Vis/NIR imaging of Multiple Asteroids Asteroid Companions

Both science cases entitled "Asteroid Companions Survey" and "Asteroid Companions Orbit Determination" use the same instruments and same observing methods. We present them in "Vis/NIR imaging of Multiple Asteroids Asteroid Companions". These key science drivers will give the most restrictive constraint on the NGAO efficiency requirement with the completion of an observation in less than 26 min (reqt #11a.3).

This science case aims at searching for companions around small solar system bodies (SSSBs) by direct imaging. Since the asteroid itself cannot be used as a reference, ephemeris calculations are necessary to be able to predict which asteroids are observable each night (and when) considering that we need 3 tip-tilt stars with an infra-red (m_{JHK}) magnitude <20 (KAON642) at less than 120 arcsec from the target. A companion with a ΔJ>5.5 at 0.5" could be detected with the NGAO system on a V<17 target. The camera used for the observations (visible or infrared) and the wavelength of observations will depend on i) the predicted brightness of the asteroid ii) the atmospheric conditions. Current AO systems do not provide a correction sufficient to detect km-sized companions around asteroids fainter than 14^{th} magnitude.

6.5.1.1 Description

The success of this science case depends essentially on the quality of the AO correction (to detect faint companion) and the number of targets observed in one night (to improve the statistic on the multiplicity rate). Current studies show that at least 6% of large (D>40 km) main-belt asteroids have a moonlet companion and less than 1% are double. The multiplicity rate for smaller asteroids (D~10 km) seems to be significantly higher (10-15%). The survey includes more than 100 asteroids and should be finalized in 3 years (3 nights per year) implying that ≥ 25 targets per 11 hour night should be observed.

Parameters	Value	Comments
Science instrument	NIR or Visible camera	
Instrument setup	FoV: 3x 3 arcsec I-z or J-H wavelength λ/3D in J and H bands, λ/2D in I and z bands,	
Target observability	At least 30 min with airmass ≤ 1.6	
Individual integration time on target	ncoadds x ind. integ. time = 1-2 min	Evaluate linearity and saturation time?
Observing efficiency	good peak SNR (>1000) in less than 26 min including 5-10 min integration time on target	Requires reading smaller array/FoV: 3" Require readout overhead? Requires ND filters: NO
Positioning precision of target	< 1"	Celestial coordinates generated using on-line servers (JPL, IMCCE)
Background estimation	Small random dither in a ~ 1 x 1 arcsec box Size of the box depends on the amplitude of the camera distortions.	Using randomly generated position or with known step Size of dither/dithering method that will minimize overheads.
Instrumental calibration	Flat field and astrometry	Internal calibration during the day, validated by regular on-sky calibrations
PSF calibration	From modeling the 2-D field-dependent profile based on star extraction, AO and C_n^2 telemetry.	Telemetry-based PSF reconstruction
Field identification	Using Guiding camera after comparison with known star catalog	Data saved in WCS format

Table 9: Summary of the observing parameters for the "Asteroid Companion Survey Search" science case

6.5.1.2 Assumptions and pre-requisites

To calculate the observing efficiency, we have made the following assumptions

- Total Exposure time ranging from 5 to 15 min for target with V magnitude ranging from 13 to 17.
- From KAON 529: pixel scale is λ/3D in J and H bands and λ/2D in I and z bands
- Targets is observed at airmass <1.6
- Angular separation between two targets is less than 10 degrees in average limiting the time lost due to slewing the telescope

The only observing challenge of this science case is the fact that the targets are moving. A tool which will provide ephemeris calculation for the asteroids and a catalog of sufficiently bright tip-tilt stars is necessary to estimate the most appropriate time to perform the observations, and the integration time (avoiding smearing effect). It is also important to remember that the wavelength of observations needs to be chosen (from visible to near infrared) taking into account the angular resolution and sensitivity provided by the system and the proper motion of the targets which will limit the integration time per frame.

6.5.1.3 Observing model

The PI and its team will need 3 nights per year over 3 year to complete this program. Assuming a weather-loss fraction of 0.25 and at least 26 min exposure time + overhead per target, at least 300 targets will be observed..

Astronomers are requesting half to full nights for this science case in classical observing mode. The astronomers will be performing the observations remotely (either at Waimea or elsewhere). The PI and the science team are responsible for the backup observing program.

6.5.1.4 Pre-observing tasks

See Section 6.6.

6.5.1.5 Observing tasks

See Section 6.8.

6.5.1.6 Post-observing tasks

See Section 6.10.

6.6 Pre-Observing Tasks for all NIR imaging observations

During the pre-observing planning process of the NIR Imaging science cases (Galactic center, multiple asteroids and exoplanets around nearby stars), the astronomer will want to perform the following actions from her/his home institute:

Astronomer	Support staff	Instrument
Task: instrument selection		
1. Review NIR camera performance parameters for anticipated use, e.g., sensitivity limit, filter, spatial scale, science field of view, etc.		1. Provides complete list of NIR camera performance parameters, including instrument distortion calibrations, detector response, filter profiles, relevant constraints for observing and setup, etc.
Science fields and targets selection		
1. The astronomer reviews main requirements affecting final selection of targets for this choice of instrument setup: e.g. maximum distance to guide stars (GS), GS brightness and morphology, telescope pointing limits, etc.		1. Provides a narrative of target selection rules applied by the AO Guide Star tool.
2a. For Galactic Center Science case Search and save coordinates for AO Natural Guide Stars within the ~ 1 arcmin x 1 arcmin centered on Sgr A*. Using appropriate catalogs and other		2. Provides an AO Guide Star tool that will search catalogs available (e.g., Vizier) and extract the coordinates, brightness (visible and NIR) and color information for a list of science field

references, the astronomer extracts the R, J, H and K band brightness for each NGS. **2b. For Multiple Asteroids and Nearby star exoplanet Science case** The astronomer prepares a list of a ~100 potential targets (asteroids or nearby stars) for the night of observations using various catalogs and current surveys. Targets will be selected based on the presence of bright tip-tilt stars. Large sample is necessary to be able to find optimal targets for all kinds of conditions during the night of observation. Using appropriate catalogs, the astronomer extracts the R, J, H and K-band brightness for each tip-tilt star and targets. **2c. For the Gas Giant Planet case** One or several optimal configurations of satellites to observe the Gas Giant were prepared using ephemeris calculations. The astronomer extracts the R, J, H and K-band brightness and the proper motion for each tip-tilt satellites. The location of the LGS "3+1" asterism is also defined.		coordinates.
		3. The GS tool will derive and save various configurations for the GS selection. • A set of selection rules will be used to quickly derive the most favorable GS configuration (e.g, based on brightness/distance, known binaries, opening angle, **TBD**).
3. Use the available tool and the observing information to derive a general NGAO configuration and check for any problems.		4. Given the characteristics of the science target(s) (e.g., number of field(s) and corrected field of view – largely based on the instrument selection/setup), a tool will identify and recommend a general configuration for the NGAO system (e.g., laser asterisms geometry, PnS on AO GS, etc.)
4. Astronomers review the target + AO GS list and might choose to keep at least 2 or 3 GS configurations per target.		5. For each science field and GS configuration, the tool will return a first-order performance metrics (based on an NGAO performance look-up table as a function of primary observing and system parameters).
5. The astronomer will use the starlist tool to save the starlist in various required formats: LCH submission format, telescope format, astronomer format, or any specific syntax required.		6. A starlist tool allows the user to easily manage the starlist information (including coordinates for science fields, science targets, AO GS configurations, acquisition reference source and science reference source).

Pick-off alignments		
1. Review the information and: • identify source(s) for field ID in R band wrt the AO GS, remembering that the AO GS will not be visible on the acquisition camera. • the methodology for sky background		1. A pick-off alignment tool simulates and overlays the location for the AO GS pick-off arms over the sources in the field.
2. Selects a geometry for the pick-off alignment for the individual AO GSs and saves it (with the starlist information - **TBC**). Reviews alignment tool choice of pick-off geometry to ensure that no vignetting occurs at any point in the observation or that any vignetting present is acceptable. Two parameters need to be defined: • field orientation • anticipated dither geometry (*these values might be easier defined in instrument coordinates as the LGS asterism needs not move wrt to the science center*).		2. A pick-off alignment tool simulates, checks and save the location for the pick-off arms for the AO GS and the LGS. Pick-off geometry is selected automatically given the location of the AO GS's, the input dither pattern, and the field orientation. The center for the LGS asterism will be the center of the instrument FOV.
Simulate NGAO performance on science fields		
1. The astronomer provides the science fields coordinate list, including individual science targets and NGS guide stars.		1. For each science field and GS configuration, the tool will return a performance metrics (based on an NGAO performance look-up table as a function of primary observing parameters and a library of PSFs).
2. The astronomer provides an observing setup including observing wavelength and spectral resolution, pixel scale, an observing date/time (or air-mass), and selects an observing conditions scenario (e.g., x% percentile seeing conditions, wind conditions)		2. Includes a library of Mauna Kea atmospheric conditions for the relevant parameters used for the AO simulations. The tool allows the user to define the expected airmass range and a range of observing conditions within the library.
3. The astronomer selects the output format for the AO performance on the science targets.		3. For each observing case, the simulation tool outputs a simulated performance at the location of the science target. The AO performance includes the values for Strehl ratio, FWHM, Ensquared Energy (assuming a pixel geometry), residual TT rms, and TBD. The tool will deliver a model PSF representative of the average AO performance over the individual exposure times of the observations with the selected observing conditions.
Simulate the instrument performance: SNR tool		
1. The astronomer provides: • The output PSF profile from the NGAO simulation tool		1. The SNR tool takes as inputs: • The output PSF profile from the NGAO simulation tool

• A spatial (and spectral?) model for the object (format TBD) • A total flux expressed in TBD photometry system (mJy, ergs s^{-1} cm^{-2})		• A spatial (and spectral?) model for the object (format TBD) • A total flux expressed in TBD photometry system (mJ, ergs s^{-1} cm^{-2})
		2. The SNR tool includes routines, data libraries and documentation for: • Sky emission flux model (airglow + continuum) • Transmission and background emission model for the telescope + AO + instrument • Model templates for the spatial (and spectral?) model for the object (format TBD)
3. The astronomer uses the tool to derive signal-to-noise ratio for selected integration time and observing setup.		3. The SNR tool estimates the signal-to-noise per pixel as well as integrated SNR, based on a model for the instrument for the observing setup. The instrument model will include: • A model for the detection noise, depending on detector readout options. • Reference sensitivity numbers for the instrument (e.g., instrument optics transmission, detector QE, % linearity vs. deep-well, zero-points) S/N estimate will be given with average, high and low sky background.
Observing sequences planning		
1. The astronomer enters or selects the observing parameters for each observing sequence for the science object: object name, target list integration time, filter selection, dither pattern (number and coordinates), spatial and spectral observing setup, etc. A good starting reference for planning the observing sequences for the science instrument is the OSIRIS Observations Planning Gui (OOP Gui). Note that the OOP Gui does not include the full set of information such as location of Guide Stars		1. The tool is used for planning the observations in all possible details, including information on targets and guide star coordinates, field orientation per science target, filter sets, dithers, sky positions, etc. The planning tool uses the coordinate information to display the location of the science fields, the guide stars, and the AO field of regard, hence allowing the user to check the field geometry in either sky or instrument coordinate systems.
2. The astronomer simulates various observing scenarios and save the final selected planning sequences.		2. The planning tool estimates the observing efficiency for the observing sequence (i.e., not including the AO acquisition or the calibration standards). The accompanying documentation provides information on observing overheads such as detector readout, dithering overhead, etc.
3. During observing, the observer will load up the observing sequences using the same tool, check these sequences		3. The planning tool will be used during observations to check the observing sequences and save the file that will be

one more time, make changes if necessary and command their execution.		used by the observing sequence execution Gui.
Calibration sequences planning		
1. The astronomer reviews the required calibration fine centering source, telluric standard, photometric standards, darks and flats, skies. TBD: case of the standard star(s) requires AO GS and LGS.		1. The documentation provides information on the required calibrations.
2. The astronomer simulates various calibration sequences and saves the planning sequences. Particularly, there could a case where additional source(s) in the science field could serve as reference for fine centering, telluric or photometric standard, and/or PSF calibrations. The source could be observed simultaneously in the science field with the on-axis imager.		2. The planning tool is used to simulate and save the instrument configuration for calibration sequences.
3. The astronomer determines the requirement for the PSF calibrations, and prepares the corresponding observing sequences.		3. Provide documentation on PSF calibration procedures and expected performance.
Laser Clearing House target submission		
1. The astronomer produces a list of all science fields requiring laser propagation including coordinate information for the science targets and the AO GS in a **TBD** format. In addition, the list includes information on brightness, color and morphology for each AO GS in **TBD** format. *At this point, we think it is not necessary to include details from 1) the observing sequences in LGS mode (yet, large offsets with LGS could require an additional pointing for LCH clearance); 2) target information for the observing sequences performed in NGS mode.*		1. The star list tool allows the user to save a star list in the coordinate and list format required for LCH.
2. The astronomer sends the list to the Observatory at least **TBD** (working) days in advance of the observations.	2. The Observatory staff uses a LCH coordination tool that collects the star list information per night (likely from formatted emails) and consolidate it (e.g., add engineering pointings or other astronomers' data). The staff uses the LCH coordination tool to send a notice message to the observer(s) that includes the target list information sent for LCH approval.	2. The star list tool allows the astronomer to submit the star list to Keck. A LCH coordination tool receives the target list from the observer. The tool has access to Keck data base for managing and using observers information for a given observing night.
3. The astronomer checks the list sent by email from Keck, and sends a formatted reply back to Keck.		3. Upon positive reviews from the astronomers, the LCH coordination tool submits the list by email to LCH.
	4. The LCH coordination tool receives	

	the times where laser propagation is precluded from LCH and format it for the observing planning and execution tools.	

Table 10: Pre-observing tasks common to all NIR imaging observations

6.7 Pre-Observing Tasks for all IFU Observations

During the pre-observing planning process of the NIR IFU science cases (Galaxy Assembly, Nearby AGNs, and Galactic center radial velocities), the astronomer will want to perform the following actions from her/his home institute:

Astronomer	Support staff	Instrument
	Task: instrument selection	
1a. Review NIR IFU performance parameters for anticipated use, e.g., sensitivity limit, wavelength, spatial and spectral resolution, science field of view, etc. 1b. Galactic Center Case: also check for changes since previous runs.		1. Provides complete list of NIR IFU performance parameters, including instrument configurations, relevant constraints for observing and setup, etc.
	Science fields and targets pre-selection	
1. Using appropriate catalogs and other references, the astronomer pre-selects science fields and individual targets including information on magnitude, color, size (region of interest), line flux, PA, etc.		
2a. For each science field, the astronomer obtains and saves coordinates for individual targets 2b. Galactic Center Case, SgrA*: 17 45 40.0409 -29 00 28.118		2. Provides information on star list and coordinates format for science field and science target.
3. Determine required S/N for targets of interest. This can be point-source, extended, per spectral channel, etc.		3. Provides an exposure time calculator to aid in sensitivity and background calculations. This should include a basic S/N calculator that uses reasonable assumptions for Strehl based on typical guide star (GS) brightness and distance, as well as background estimates from models. (There could be a switch to allow more detailed calculations given specific fields. The first step is a simple feasibility check.)
	Science fields and targets selection	
1. The astronomer reviews main requirements affecting final target selection for this choice of instrument setup: e.g. maximum distance to GS, GS brightness and morphology, number of available GS (if less than 3), telescope pointing limits, etc.		1. Provides a narrative of target selection rules applied by the AO Guide Star tool.
2. For each science field, search and save coordinates for possible AO Natural Guide Stars		2. Provides an AO Guide Star tool that will search catalogs available on the internet (ADS, NASA, etc) and extract the coordinates, brightness (visible and NIR) and color information for a list of science field coordinates.

		3. For each science field information set, the GS tool will derive and save various configurations for the GS selection. • Each science field might present various possibilities for the AO GS configurations. • A set of selection rules will be used to quickly derive the most favorable GS configurations (e.g, based on brightness/distance).
4. Use the available tool and the observing information to derive general NGAO configuration and check for any problems.		4. Given the characteristics of the science target (e.g., corrected field of view – largely based on the instrument selection/setup), a tool will identify and recommend a general configuration for the NGAO system (e.g., laser asterisms geometry, PnS on AO GS, etc.)
5. Astronomers review the target + AO GS list and prioritize their target list based on science priority, anticipated image quality, and other relevant parameters. The astronomer might choose to keep at least 2 or 3 GS configurations for each science field.		5. For each science field and GS configuration, the tool will return a first-order performance metrics (based on a NGAO performance look-up table as a function of primary observing and system parameters).
6. Given the possible complexity of the star list the astronomer will use a tool to manage, view and consolidate the star list information. The list can be edited by the astronomer to add point-like source coming from other bibliography source; or to edit specific information. The astronomer will use this tool to save the starlist in various required format: LCH submission format, telescope format, astronomer format, or any specific syntax required.		6. A starlist tool allows the user to easily manage the starlist information (including coordinates for science fields, science targets, AO GS configurations, acquisition reference source and science reference source).
	Pick-off alignments	
1a. Review the sources in the science fields and identify: - which source(s) will serve as a reference for fine centering (if applicable) - the methodology for sky background 1b. For the Galactic Center Case, the sky background must be obtained from the science field due to strong emission features in the sky at this position.		1. A pick-off alignment tool simulates and overlays the location for the LGS and AO GS pick-off arms over the sources in the field.
2. Selects geometry for the pick-off alignment for the individual AO GS and saves it (with the starlist information - **TBC**). Two parameters need to be defined: field orientation of the IFU (PA) and anticipated dither geometry (*these values might be easier defined in instrument coordinates as the LGS needs not to move wrt to the science*		2. A pick-off alignment tool simulates, checks and saves the location for the pick-off arms for the AO GS and the LGS.

center).		
Simulate NGAO performance on science fields		
1. The astronomer provides the science fields coordinate list, including individual science targets and NGS guide stars.		1. For each science field and GS configuration, the tool will return a performance metrics (based on a NGAO performance look-up table as a function of primary observing parameters and a library of PSFs).
2. The astronomer provides an observing setup including observing wavelength and spectral resolution, an observing date/time (or air-mass), and selects an observing conditions scenario (e.g., x% percentile seeing conditions, wind conditions, etc.)		2. Includes a library of Mauna Kea atmospheric conditions for the relevant parameters used for the AO simulations. The tool allows the user to define the expected air mass range and a range of observing conditions within the library.
3. The astronomer selects the output format for the AO performance on the science targets.		3. For each observing case, the simulation tool outputs a simulated performance at the location of the science target. The AO performance includes the values for Strehl ratio, FWHM, Ensquared Energy (assuming a pixel geometry), residual TT rms, and TBD. The tool will deliver a model PSF representative of the average AO performance over 5 min (or a user-selected observing time, e.g., 15 min. for G.C.) with the selected observing conditions.
Simulate the instrument performance: SNR tool		
1. The astronomer provides: • The output PSF profile from the NGAO simulation tool • A spatial (and spectral?) model for the object (format TBD, but examples might include selecting from typical galaxy and stellar spectral templates as well as standard $r^{1/4}$ and exponential surface brightness profiles with specified scale lengths) • A total flux expressed in TBD photometry system (mJ, ergs.s^{-1}, mag/ sq. arcsec)		1. The SNR tool takes as inputs: • The output PSF profile from the NGAO simulation tool • A spatial (and spectral?) model for the object (format TBD) • A total flux expressed in TBD photometry system (mJ, ergs.s^{-1})
		2. The SNR tool includes routines, data libraries and documentation for: • Sky emission flux model (airglow + continuum) • Transmission and background emission model for the telescope + AO + instrument • Model templates for the spatial (and spectral?) model for the object (format TBD)
3. The astronomer uses the tool to		3. The SNR tool estimates the signal-

derive signal-to-noise ratio for selected integration time and observing setup.		to-noise per pixel as well as integrated SNR, based on a model for the instrument for the observing setup. The instrument model will include: • A model for the detection noise, depending on detector readout options. • Reference sensitivity numbers for the instrument (e.g., instrument optics transmission, detector QE, % linearity vs. deep-well, zero-points) • Median SNR and for average, low and bright background
Observing sequences planning		
1. The astronomer enters or selects the observing parameters for each observing sequence for the science object: object name, target list integration time, filter selection, dither pattern (number and coordinates), spatial and spectral observing setup, etc. A good starting reference for planning the observing sequences for the science instrument is the OSIRIS Observations Planning GUI (OOP GUI). Note that the OOP GUI does not include the full set of information such as location of Guide Stars		1. The tool is used for planning the observations in all possible details, including information on targets and guide star coordinates, field orientation per science target, filter sets, dithers, sky positions, etc. The planning tool uses the coordinate information to display the location of the science fields, the guide stars, and the AO field of regard, hence allowing the user to check the field geometry in either sky or instrument coordinate systems. The tool generates a finding chart for the guider field of view using e.g., DSS, etc. This can be saved/printed and used while observing at the telescope to aid in field identification.
2. The astronomer simulates various observing scenarios and saves the final selected planning sequences.		2. The planning tool estimates the observing efficiency for the observing sequence (i.e., not including the AO acquisition or the calibration standards). The accompanying documentation provides information on observing overheads such as detector readout, dithering overhead, etc.
3. The astronomer estimates offsets needed to move from the setup object field and the science field (if applicable)	3. Provide the astronomer with the latest estimates of the offset between the field centers of the IFU and the imager, and the orientations on-sky of each.	
4. During observing, the observer will load up the observing sequences using the same tool, check these sequences one more time, make changes if necessary and command their execution.		4. The planning tool will be used during observations to check the observing sequences and save the file that will be used by the observing sequence execution GUI.
Calibration sequences planning		
1. The astronomer reviews the required calibration: fine centering source, telluric standard, photometric standards, darks and flats, skies, PSF.		1. The documentation provides information on the required calibrations. (E.g., flatfields and darks should be taken by the observatory and kept as part of a standard calibration

TBD: case of the standard star(s) requires AO GS and LGS.		library.)
2. The astronomer simulates various calibration sequences and saves the planning sequences. Particularly, there could be a case where additional source(s) in the science field could serve as reference for fine centering, telluric or photometric standard, and/or PSF calibrations.		2. The planning tool is used to simulate and save the instrument configuration for calibration sequences.
3. The astronomer determines the requirement for the PSF calibrations, and prepares the corresponding observing sequences.		3. Provide documentation on PSF calibration procedures and expected performance.
	Laser Clearing House target submission	
1. The astronomer produces a list of all science fields requiring laser propagation including coordinate information for the science targets and the AO GS in a TBD format. In addition, the list includes information on brightness, color and morphology for each AO GS in TBD format. *At this point, we think it is not necessary to include details from 1) the observing sequences in LGS mode (yet, large offsets with LGS could require an additional pointing for LCH clearance); 2) target information for the observing sequences performed in NGS mode.*		1. The star list tool allows the user to save a star list in the coordinate and list format required for LCH.
2. The astronomer sends the list to the Observatory at least TBD (working) days in advance of the observations.	2. The Observatory staff uses a LCH coordination tool that collects the star list information per night (likely from formatted emails) and consolidates it (e.g., add engineering pointings or other astronomers' data). The staff uses the LCH coordination tool to send a notice message to the observer(s) that includes the target list information sent for LCH approval.	2. The star list tool allows the astronomer to submit the star list to Keck. A LCH coordination tool receives the target list from the observer. The tool has access to Keck database for managing and using observers' information for a given observing night.
3. The astronomer checks the list sent by email from Keck, and sends a formatted reply back to Keck.		3. Upon positive reviews from the astronomers, the LCH coordination tool submits the list by email to LCH.
	4. The LCH coordination tool receives the times where laser propagation is precluded from LCH and formats it for the observing planning and execution tools.	
5. Maintain records of the location, brightness and SNR (anticipated and observed) of the guide stars and spectropscopic standards, as well as the instrumental setup, field location and orientation, and full star list as submitted to space command, so that subsequent similar runs may be rapidly		

and efficiently set up.		

Table 11: Pre-observing tasks common to all IFU observations

6.8 Observing Tasks for all NIR Imaging Observations

Astronomer	Support staff	Instrument
Target selection		
1. The astronomer selects the next science target among the planned observations. The astronomer checks the target field status for observation planning: target field uptime, laser traffic control clearance during the anticipated observing time, etc.	1. The support staff checks the science field observability status: target field uptime, target submitted to LCH, LCH no-propagation windows, laser traffic control clearance, etc.	1. A tool provides information and status on observability using LGS for the science targets. The tool displays: telescope limits and target uptime, target LCH status, laser traffic control status on target, etc.
Field identification		
1. The astronomer prepares the necessary information to review and ID the field in the R wavelength range: R-band chart, etc. Note that for some science cases (e.g., Galactic Center), the initial setup field is not necessarily the science target. (GC case: Center on nearby guide star, USNO-A3.0 0609-0602733, r=14.0, sep 19.3")	1. Command telescope slew and request setup for NGAO (acquisition, laser, AO, pick-off alignment, instrument) based on observing sequences information.	1. Given selection of instrument, coordinates of science target and guide stars, pick-off alignment information, the tool outputs a configuration for NGAO sub-systems (acquisition, laser, AO, etc). This tool can run in a preview mode in the afternoon during observing checkout. Execute setup commands for NGAO (acquisition, laser, AO, GS pick-off alignment, instrument) based on observing sequences information.
2. Once the telescope is pointing at the science field and the field rotated as requested, the astronomer helps ID the field using the acquisition camera display, a catalog image of the same field and any additional information (e.g., images from previous observations of the same field). Astronomers use the AO guide stars as a reference in the R-band.	2. Assesses whether the telescope pointing needs to be adjusted on a nearby reference star and find the star *(note that this could be fully automated by inserting a telescope pointing star for every science field)*; Based on the AO guide stars, ID the field using the acquisition camera display, a catalog image of the same field and any help from the acquisition system and the astronomer.	2. The acquisition system displays simultaneously the on-sky recorded image, a catalog image of the field at the same wavelength, orientation and scale, and the coordinates and information for the AO guide stars. The tool attempts to cross-correlate the two fields and ID the brightest objects. The ID information for the brightest guide stars (GS) in the field is overlaid to the recorded image to be viewed by the astronomer and support staff. The process will be confirmed by the telescope operator.
Science fields and guide stars acquisition		
1. Review the science instrument setup.	1. Monitors the progress on the science field acquisition by checking that the AO GS are registered with the location of the probe arms (e.g., counts on LOWFS). *Note that this is an off-axis acquisition where the pointing origin is re-defined for each new science field—GS geometry (not currently implemented with Keck AO).*	1. The acquisition software (MAGIQ) estimates the telescope offset and applies this offset. The science field acquisition is performed by registering at least one AO GS with a pixel location on the acquisition camera (pointing origin) such that the science target is registered with the pointing origin corresponding to the center of the science detector.
2. Monitor the AO performance during acquisition and wait for go-ahead from support staff and system.	2. Monitors the progress of NGAO acquisition. There should not be any manual acquisition step as it generally slows down efficiency and reliability. If the	2. The NGAO software commands the LGS and LOWFS acquisition, closes the loops and optimizes the system performance. The software informs on "AO

	chosen configuration does not give good correction, a second one will be chosen. Gives the go-ahead to the astronomer when NGAO acquisition completes.	readiness" when NGAO acquisition is complete and performance is optimized.
Fine centering (if necessary)		
1. Pre-observing offset (if necessary). Astronomer notifies SA and OA of required offset from the AO GS or other reference field to place the science target near the center of the detector.	1. Command telescope slew	
2. Fine centering is checked by observing the science target (or any identified source in the field) bright enough and visible in one sky-subtracted integration; Case 1: the AO GS are well centered for the pre-defined pick-off coordinates: the fine centering checkout observations will be performed without pre-offset. Case 2: the AO GS are all de-centered for the pre-defined pick-off coordinates: the fine centering checkout observations will be performed after a pre-offset estimated from the average positioning error.	2. Monitors the execution of the automated observing sequences for Case 1. Inform the observer and coordinate/confirm the re-centering actions for Case 2.	1. The NGAO system identifies the source(s) used for fine centering from the observer star list information.
2. Blind fine centering: when the science target (or any identified source in the field) is not bright enough and is not visible in one sky-subtracted integration; Case 1: the AO GS are well centered for the pre-defined pick-off coordinates: science observations will be performed without pre-offset. Case 2: the AO GS are all de-centered for the pre-defined pick-off coordinates: science observations will be performed after a pre-offset estimated from the average positioning error.	2. Monitors the execution of the automated observing sequences for Case 1. Inform the observer and coordinate/confirm the re-centering actions for Case 2.	1. The NGAO system uses the AO GS coordinates to center the field. 2. The NGAO system may re-position the pointing center to minimize the centering error.
3. If necessary, (e.g., in case of G.C. where one needs to keep IRS7 off the array so it does not saturate) update offset to place tracer star at desired pixel position on science detector.	3. Command offset	
Observations on-source science fields		
1. Load the observing sequences	1. Monitors the execution of the observing sequences	1. NGAO system (including instrument) provides the tools to load, execute and monitor the progress for the observing sequences.
2. Monitors the execution of the observing sequences.	2. Monitors system performance variables such as LOWFS photometry and AO performance.	
	3. Monitors NGAO health and fault detector.	

Dither on the science field		
1. Monitors the execution of the observing sequences. The dither pattern is defined in the observing sequences and the pattern cannot be changed on-the-fly. The pattern can be defined in sky or instrument coordinate systems for a given sky orientation. A sub-pixel dithering pattern may be required to recover spatial information for the shortest observing wavelengths.	1. Monitors the execution of the observing sequences	1. The NGAO system dithers the science targets around the science array with minimal overhead - repositioning by steering the science light path only, for move if the narrow-field DM FoV permits - or repositioning by steering the common light path with the woofer DM (case dither amplitude is larger than narrow-field DM FoV) - See KAON 558
2. Monitors the image quality as frames are being recorded and display. TBD:: requirements for the on-the-fly DRP.		
Calibrations: photometry		
1. Performs the necessary calibrations required by the data reduction pipeline.	1. Provides support for the required calibrations.	1. Provides documentation, characterization and support for the required calibrations.
2. Load and execute the observing sequence for the photometric calibrations.		
3. Calibrate the PSF possibly using PSF reconstruction based on ancillary telemetry (WFC and C_n^2 data).		3. The NGAO system records ancillary data and provide the tool for reconstructing the PSF.

Table 12: Observing tasks common to all NIR imaging observations

6.9 Observing Tasks for all IFU Observations

Astronomer	Support staff	Instrument
Target selection		
1. The astronomer selects the next science target among the planned observations. The astronomer checks the target field status for observation planning: target field uptime, laser traffic control clearance during the anticipated observing time, etc.	1. The support staff checks the science field observability status: target field uptime, target submitted to LCH, LCH no-propagation windows, laser traffic control clearance, etc.	1. A tool provides information and status on observability using LGS for the science target. The tool displays: telescope limits and target uptime, target LCH status, laser traffic control status on target, etc.
Field identification		
1. The astronomer prepares the necessary information to review and ID the field in the R wavelength range: R-band finding chart from the pre-observing planning tool, etc. In some cases (e.g., Galactic Center), this may mean preparing information to ID the field of a nearby bright star to center up on before offsetting to the science field.	1. Command telescope slew and request setup for NGAO (acquisition, laser, AO, instrument) based on observing sequences information.	1. Given selection of instrument, coordinates of science target and guide stars, the tool outputs a configuration for NGAO sub-systems (acquisition, laser, AO, etc). This tool can run in a preview mode in the afternoon during observing checkout. Execute setup commands for NGAO (acquisition, laser, AO, GS pick-off alignment, instrument) based on observing sequences information.
2. Once the telescope is pointing at the science field (or a suitable setup field) and the field is rotated as requested, the astronomer helps ID the field using the acquisition camera display, a catalog image of the same field and any	2. Assesses whether the telescope pointing needs to be adjusted on a nearby reference star and find the star *(note that this could be fully automated by inserting a telescope pointing star for every science field)*;	2. The acquisition system displays simultaneously the on-sky recorded image, a catalog image of the field at the same wavelength, orientation and scale, and the coordinates and information for the AO guide stars.

additional information (e.g., images from previous observations of the same field). Astronomers use the AO guide stars as a reference in the R-band. TBD if simultaneous imaging will be possible.	Based on the AO guide stars, ID the field using the acquisition camera display, a catalog image of the same field and any help from the acquisition system and the astronomer.	The tool attempts to cross-correlate the two fields and ID the brightest objects. The ID information for the brightest GS in the field is overlaid to the recorded image to be viewed by the astronomer and support staff.
3. (If required, e.g., in the case of setup on a nearby reference field) Produce the offset required to put the science target at the desired location on the detector. This offset will most likely be computed from existing NIR imaging or from a previous collapsed IFU datacube.	3. Monitor NGAO performance during the offset	
Science fields and guide stars acquisition		
1. Review the science instrument setup.	1. Monitors the progress on the science field acquisition by checking that the AO GS are registered with the location of the probe arms (e.g., counts on LOWFS). *Note that this is an off-axis acquisition where the pointing origin is re-defined for each new science field—GS geometry (not currently implemented with Keck AO).*	1. The acquisition software (MAGIQ) estimates the telescope offset and applies this offset. The science field acquisition is performed by registering at least one AO GS with a pixel location on the acquisition camera (pointing origin) such that the science target is registered with the pointing origin corresponding to the center of the science detector.
2. Monitor the AO performance during acquisition and wait for go-ahead from support staff and system.	2. Monitors the progress of NGAO acquisition. There should not be any manual acquisition step as it generally slows down efficiency and reliability. Gives the go-ahead to the astronomer when NGAO acquisition completes.	2. The NGAO software commands the LGS and LOWFS acquisition, closes the loops and optimizes the system performance. The software informs on "AO readiness" when NGAO acquisition is complete and performance is optimized.
Fine centering		
1. Fine centering is checked by observing the science target (or any identified source in the field) bright enough and visible in one sky-subtracted integration; Case 1: the AO GS are well centered for the pre-defined pick-off coordinates: the fine centering checkout observations will be performed without pre-offset. Case 2: the AO GS are all de-centered for the pre-defined pick-off coordinates: the fine centering checkout observations will be performed after a pre-offset estimated from the average positioning error.	1. Monitors the execution of the automated observing sequences for Case 1. Inform the observer and coordinate/confirm the re-centering actions for Case 2.	1. The NGAO system identifies the source(s) used for fine centering from the observer star list information.
1. Fine centering is checked by observing the position of a science target or reference field visible in one sky-subtracted integration (e.g., SgrA*), at the center of the imager, and then offsetting to place the science target at the center of the IFU detector.	1. Monitors the execution of the automated observing sequences for Case 1. Inform the observer and coordinate/confirm the re-centering actions for Case 2.	1. The NGAO system identifies the source(s) used for fine centering from the observer star list information.

The offset on-sky between the imager and the spectrograph will need to be known to 2 spaxel precision (~40-60mas). Case 1: the AO GS are well centered for the pre-defined pick-off coordinates: the fine centering checkout observations will be performed without pre-offset. Case 2: the AO GS are all de-centered for the pre-defined pick-off coordinates: the fine centering checkout observations will be performed after a pre-offset estimated from the average positioning error.		
1. Blind fine centering: when the science target (or any identified source in the field) is not bright enough and is not visible in one sky-subtracted integration; Case 1: the AO GS are well centered for the pre-defined IFU coordinates: science observations will be performed without pre-offset. Case 2: the AO GS are all de-centered for the pre-defined IFU coordinates: science observations will be performed after a pre-offset estimated from the average positioning error.	1. Monitors the execution of the automated observing sequences for Case 1. Inform the observer and coordinate/confirm the re-centering actions for Case 2.	1. The NGAO system uses the AO GS coordinates to center the field. 2. The NGAO system may re-position the pointing center to minimize the centering error.
Observations on-source science fields		
1. Load the observing sequences	1. Monitors the execution of the observing sequences.	1. NGAO system (including instrument) provides the tools to load, execute and monitor the progress for the observing sequences.
2. Monitors the execution of the observing sequences.	2. Monitors system performance variables such as LOWFS photometry and AO performance.	
	3. Monitors NGAO health and fault detector.	
Dither on the science field		
1. Monitors the execution of the observing sequences. The dither pattern is defined in the observing sequences and the pattern cannot be changed on-the-fly. The pattern can be defined in sky or instrument coordinate systems for a given sky orientation.	1. Monitors the execution of the observing sequences.	1. The NGAO system dithers the science targets around the science array with minimal overhead - by repositioning the narrow-field DM (case dither amplitude is small) to adjust the science light path, if the DM FoV permits - or by steering the common light path with the woofer DM and repositioning the LOWFS pick-offs (case dither amplitude is larger than tweeter DM FoV) - or by slewing the telescope and repositioning all pick-offs (case for offsets > 30") - See KAON 558
2. Monitors the image quality as frames are being recorded and display.		TBD: requirements for the on-the-fly DRP (minimum—allow observer to

		select a "sky" frame and provide sky subtracted data cubes of each exposure).
Calibrations: telluric and photometry		
1. Performs the necessary calibrations required by the data reduction pipeline.	1. Provides support for the required calibrations. The requirements for the flat-field and spectral calibrations required by the data reduction pipeline will be detailed during the study and design of the IFU.	1. Provides documentation, characterization and support for the required calibrations.
2. Load and execute the observing sequence for the telluric and photometric calibrations.		
3. Calibrate the PSF possibly using one of these methods: 1) PSF monitoring using dedicated PSF star observations throughout the night, and/or 2) PSF reconstruction based on ancillary telemetry (WFC and C_n^2 data), and/ or 3) using spatially unresolved spectral features (see, e.g., Davies et al. 2006). *The first scenario is costly to science as it requires dedicating observing time at regular intervals off-target to obtain PSF information. Extrapolating the PSF measured on one location to any location in the corrected field has been demonstrated (Britton 2006).*		3. The NGAO system records ancillary data and provides the tool for reconstructing the PSF.
Data reduction pipeline		
1. Astronomers use Quicklook DRP to assess the quality of the data.		

Table 13: Observing tasks common to all IFU observations

6.10 Post-Observing Tasks for all Key Science Drivers

Astronomer	Support staff	Instrument
Nightly data saving		
1. backup the nightly data (science, calibrations and quality logs): - raw and reduced science data - raw and reduced calibrations data - intermediary and final products for PSF calibrations and reconstruction - image quality monitoring data (e.g., TBD time averaged of rms wavefront error, LOWFS photometry, C_n^2 profile, seeing) - system status monitoring data (e..g, pick-off coordinates, telescope coordinates, system faults) - Acquisition camera data per targets with LGS spot position and brightness and NGS star		1. All data used for data reduction, calibrations and scientific analysis are organized hierarchically, referenced and stored in one location, accessible by the user for backup systems: A copy of the entire data set is archived at the Observatory.
Data reduction: PSF calibration post-processing		
1. Astronomers review the reconstructed PSF for each individual	1. The support staff monitors the cron jobs that produce the PSF calibration	1. The system produces a PSF calibration file by reconstructing the

integration frame.	files either in pseudo-real time or after the observing night.	time-averaged PSF for each individual observation file (using NGAO telemetry data and C_n^2 profile). PSF reconstruction methods and intermediary and final PSF calibrations products are TBD.
Astronomical data reduction		
1. Astronomers use the Astronomical DRP to produce the final version of the reduced data used for data analysis. *Requirements: TBD (should be part of the instrument PD)*		

Table 14: Post-observing tasks common to all Key Science drivers

Save data:

The generic data product includes:

- The raw science and calibration data
- The reduced science and calibration data
- The PSF reconstruction data from the WFC and Cn2 profiler telemetry, if applicable
- The image quality monitoring data (SR, EE, flux on LOWFS and laser return, fault events log, etc)

The observatory will save and store at least one copy of the entire set of the data product, defined with the observer. The requirements for the automated archive of the NGAO data will be studied and developed during the NGAO preliminary design. The archived data will be proprietary and the release mechanism for technical or scientific purpose after a certain delay will be defined in the Preliminary Design phase of NGAO.

7 Other Science Drivers

A number of science drivers were also defined in the SCRD. Sample observations for these are less likely to drive the NGAO design including the OOCD. One case not defined in the SCRD which will drive the OOCD is the case of science with the Keck Interferometer.

7.1 Interferometer Science

Table 15 lists the current and planned science modes of the Keck Interferometer. NGAO operations must support all of these modes, with the exception of nulling. NGAO must provide at least the same observing efficiency, sky coverage and performance as the current Keck AO systems for interferometry. The NGAO requirements for interferometry are discussed in KAON 428 and are documented in the System Requirement Document (KAON 456; see the optical requirements).

Table 15: Current and planned Keck Interferometer science modes
(nulling is crossed out since it need not be supported by NGAO)

Observing Mode	Science λ	Stabilization	AO Modes	Optical Interface with AO			Status
Visibility (V^2)	H,K,L	J,H	NGS R=12	Coude	Single Star	Collimated	Operational
			LGS R=14				2010
~~Nulling~~	~~N~~	~~H~~	~~NGS R=12~~	~~Coude~~	~~Dual Pupil~~	~~Collimated~~	~~Operational~~
Self Phase Referencing V^2	H,K	J,H	NGS R=12		Single Star	Collimated	Operational
			LGS R=14				2010
Dual Field Phase Referencing V^2	H,K	J,H	NGS R=12 LGS R=14	Coude	Dual Star	Focus	2010
Astrometry	H,K	J,H	NGS R=12 LGS R=14	Coude	Dual Star	Focus	2010
OHANA V^2	H,K	NA	NGS	Fiber Optics	Single Star	Focus	Demonstrated

NGAO will be used in several different science modes with the Interferometer; the associated NGAO system configurations are shown in Table 4 of KAON 642. In normal squared visibility (V^2), self phase referencing (SPR) or OHANA interferometer modes the science target is on-axis and the NGAO system could be used in NGS mode for relatively bright science targets or in LGS mode for fainter science targets. In both NGS and LGS mode the NGAO rotator could be used in either fixed field or fixed pupil mode. For dual field phase referencing (DFPR) or astrometric interferometer science NGAO could be used in either NGS or LGS modes; in both cases the field would have to be kept fixed.

Interferometer observations will likely continue to be performed in service observing mode where the NASA Exoplanet Science Institute (NExScI) prepares the observing plan in collaboration with the astronomer and WMKO carries out the observations. WMKO still needs to develop observing strategies and tools for LGS AO science with the interferometer (see KAON 613) but once these are in place only minor changes are expected for NGAO (since the limiting AO magnitudes and capabilities will likely be set by the non-NGAO system). NGAO will of course need to support these observing strategies.

The observing sequence similarities between NGAO and the existing Keck AO systems can be further understood by the comparison between the hardware. The NGAO NGS WFS will play the same role as the existing Keck AO WFS in NGS mode. In LGS mode the NGAO tip-tilt (focus-astigmatism) sensor and truth wavefront sensor (TWFS), which use light from the same NGS, will play the same role as the existing Keck AO tip-tilt sensor and low bandwidth wavefront sensor which also use light from the same NGS. The point of the above comparison is to highlight the fact that NGS acquisition in both NGS and LGS mode will be very similar for NGAO and the existing Keck AO systems. These NGS must be on-axis for fixed pupil mode and can be on- or off-axis in fixed field mode.

The use of the NGAO LGS science asterism will be no different for interferometer science. There is no need to use the other two NGAO tip-tilt sensors or to use any of the three point-and-shoot lasers since the performance delivered to the interferometer will already be higher than for the non-NGAO system.

Table 16 lists the interferometer science requirements.

Table 16: Interferometer science requirements

#	Science Performance Requirement	AO Derived Requirements	Discussion
1	***YSO disks and PMS binaries***		
1.1	*Sensitivity*: SNR for fringe tracking is ≥ 10 for near-by YSO candidates (K ≤ 10 and H ≤ 9 in 5-pixel dispersion mode).	Acceptable AO performance for R ≤ 12 (NGS) & R ≤ 14 (LGS)	
1.2	*Spectral region:* Required wavelength range 1 – 4 microns.	AO system must transmit J, H, K & L bands	J band is not used for science, but used for IR angle tracking in the J & H band.
1.3	*Spectral resolution:* up to R=1800 in the K band (All but one mode uses much lower spectral resolution)		
1.4	*Field-of-view*: up to 1 arcminute diameter		
1.5	The interferometer output of NGAO must be polarization matched to the interferometer output of the AO system on the other telescope in order to produce ≤ 3º of differential s-p phase shift	The current KI achieves polarization matching by keeping the number, angle and coatings of all reflections the same in the beam trains from each telescope. The differential s-p phase shift in the current KI is measured at 6º resulting in a loss in V^2 of 0.003.	
1.6	The interferometer output of NGAO must have the same pupil rotation as the interferometer output of the		

	AO system on the other telescope		
1.7	The interferometer output of NGAO must have the same image rotation as the interferometer output of the AO system on the other telescope		
1.8	The interferometer output of NGAO must have the same longitudinal chromatic dispersion as the interferometer output of the AO system on the other telescope	Transmissive optics fabricated from different materials can have different amounts of longitudinal chromatic dispersion resulting in the loss of fringe visibility	
1.9	The ratio of the Strehls from the interferometer output of NGAO and the interferometer output of the AO system on the other telescope must be ≤ 1.2 and ≥ 0.9.	A Strehl mismatch of 22% or an intensity ratio of 1.22 results in a V^2 loss of 0.010.	
1.10	NGAO must be able to accommodate the accelerometers needed to support the Interferometer	On the current AO bench one accelerometer is placed near the telescope focus and another near the output to the DSM. These are used to measure vibration along the optical path and are used in the fringe tracker control system. The accelerometer acquisition system is housed in an electronics rack in the AO electronics vault.	
1.11	NGAO or NGAO in combination with a modified DSM must be capable of supporting the laser metrology beams from the interferometer	These metrology beams are a potential source of background light on the wavefront sensors	
1.12	NGAO must incorporate the required tools and tolerances to support alignment to the interferometer	For example, the current AO bench hosts a corner cube to aid in aligning the interferometer to the optical axis of the AO system and telescope	
1.13	NGAO or NGAO in combination with a modified DSM must provide a collimated 100 mm diameter beam to the interferometer	In the current AO system a removable (on a translation stage) dichroic beamsplitter, located between the deformable mirror and second off-axis parabola, folds the collimated beam to the DSM	
1.14	The rms residual tilt at the NGAO system output to the interferometer should be ≤ 0.007” for TBD guide star.		

1.15	*Narrow field imaging:* diffraction limited at J, H, K & L bands	Wavefront error 170 nm or better	
1.16	Bright magnitude limit: Required to observe targets as bright as R ~ 0	System should have adequate ND filters to accommodate bright target observations	
1.17	Tracking performance: Target drift should be ≤ 10 milliarcseconds in 20 minutes	KAT offloading to AO at 1Hz & DAR corrections are required.	
1.18	Target acquisition efficiency: should be better or same as the current AO performance	Since K1 will have the current system, NGAO shouldn't take more time for target acquisition	
1.19	Target acquisition tools	Tools to acquire and offload any residual offsets between AO system and the science instrument at the basement	
1.20	IR throughput loss	TBD	
1.21	IR emissivity	TBD	
1.22	Vibrations:	TBD	
1.23	Simultaneous seeing measurement tool		
1.24	The NGAO AO system shall not exceed a thermal dissipation budget, into the dome environment, of 100 W		Instrument Baseline Requirements, KAON 572, requirement 8.2.1.3
1.25	The NGAO laser system shall not exceed a thermal dissipation budget, into the dome environment, of 100 W		Instrument Baseline Requirements, KAON 572, requirement 8.2.1.3
1.26	The NGAO AO system shall not exceed a thermal dissipation budget at the top-end of the telescope, into the dome environment, of 50 W		Instrument Baseline Requirements, KAON 572, requirement 8.2.1.3
2	***LGS science: Galactic center & AGN***		
2.1	*Sensitivity*: SNR for fringe tracking is ≥ 10 for near-by AGN & galactic center objects (K ≤ 15 in 5-pixel dispersion mode).	Acceptable AO performance for R ≤ 14	
2.2 through 2.15	Same as 1.1 through 1.15		
3	***Astrometry: AGN, Galactic center & Exoplanets***		

3.1	*Sensitivity*: SNR for fringe tracking is ≥ 10 for near-by AGN & galactic center objects (K ≤ 15 in 5-pixel dispersion mode).	Acceptable AO performance for R ≤ 14	
3.2 through 3.15	Same as 1.1 through 1.15		

7.2 NGS mode

The NGS mode will be used to observe bright on-axis targets or target close to bright reference. Io (mv=5) and Titan (mv=8) are perfect on-axis targets to be imaged in NGS mode. In this case, we will take full advantage of the better AO corrections compared with the current Keck II AO system. Low-mass companions around bright and close stars (V<12) could take also advantage of a pure NGS mode.

The observing task of this secondary observation mode will be implemented in OOCD v2.0.

7.3 Fixed-pupil mode

KAON 666 describes the options for fixed pupil mode with NGAO. We anticipate using option #3, using the on-axis NGS WFS as a LOWFS/TWFS, and the observing scenario described here is for this specific case. However, there are advantages to option #1, using one, two or three off-axis LOWFS that track with the field, and this case should be considered in more detail if it can be implemented with little additional cost.

7.3.1 Pre-observing tasks

See Section 6.6

7.3.2 Observing tasks

Astronomer	Support staff	Instrument
Target selection		
1. The astronomer selects the next science target among the planned observations. The astronomer checks the target field status for observation planning: target field uptime, laser traffic control clearance during the anticipated observing time, etc.	1. The support staff checks the science field observability status: target field uptime, target submitted to LCH, LCH no-propagation windows, laser traffic control clearance, etc.	1. A tool provides information and status on observability using LGS for the science targets. The tool displays: telescope limits and target uptime, target LCH status, laser traffic control status on target, etc.
Field identification		
1. The astronomer prepares the necessary information to review and ID the field in the R wavelength range: R-band chart, etc.	1. Command telescope slew and request setup for NGAO (acquisition, laser, AO, pick-off alignment, instrument) based on observing sequences information.	1. Given selection of instrument, number and coordinates of science targets and guide stars, pick-off alignment information, the tool output a configuration for NGAO sub-systems (acquisition, laser, AO, etc). This tool can run in a preview mode in the afternoon during observing checkup. Execute setup commands for NGAO (acquisition, laser, AO, pick-off alignment, instrument) based on observing sequences information. Field rotator is set to keep sky PA fixed throughout field ID and acquisition.
2. Once the telescope is pointing at the science field and the field rotated as requested, the astronomer helps ID the field (with field rotator on) using the	2. Assesses whether the telescope pointing needs to be adjusted on a nearby reference star and find the star *(note that this could be fully automated*	2. The acquisition system displays simultaneously the on-sky recorded image, a catalog image of the field at the same wavelength, orientation and

acquisition camera display, a catalog image of the same field and any additional information. Astronomers use the AO guide stars as a reference in the R-band.	*by inserting a telescope pointing star for every science field)*; Based on the AO guide stars, ID the field using the acquisition camera display, a catalog image of the same field and any help from the acquisition system and the astronomer.	scale, and the coordinates and information for the AO guide stars. The tool attempts to cross-correlate the two fields and ID the brightest objects. The ID information for the brightest GS in the field is overlaid to the recorded image. The process will be confirmed by the telescope operator
Science fields and guide stars acquisition		
1. Review the science instrument setup (including any sub-array readout settings).	1. Case 1 (NGS WFS used as on-axis LOWFS): Monitors the progress on the science field acquisition by checking that the AO GS is registered with the pointing origin (e.g., counts on NGS WFS). *or* Case 2 (off-axis LOWFS that track with the field): Monitors the progress on the science field acquisition by checking that the AO GS is registered with the location of the probe arms (e.g., counts on LOWFS).	1. The acquisition software (MAGIQ) estimates the telescope offset and applies this offset. The science field acquisition is performed by registering at least one AO GS with a pixel location on the acquisition camera (pointing origin) such that the science target(s) are registered with the pointing origins corresponding to the center of the science detector(s).
2. Monitor the AO performance during acquisition and wait for go-ahead from support staff and system!	2. Monitors the progress of NGAO acquisition. There should not be any manual acquisition step as it generally slows down efficiency and reliability. If the chosen configuration does not give good correction, a second one (if available) will be chosen. Gives the go-ahead to the astronomer when NGAO acquisition completes.	2. The NGAO software commands the LGS and LOWFS acquisition, closes the loops and optimizes the system performance. The software informs on “AO readiness” when NGAO acquisition is complete and performance is optimized.
Fine centering		
1. Fine centering is checked by observing the (unsaturated) on-axis science target; Case 1: the target is well-centered ($<1/10^{th}$ pixel?) on the central pixel of the NIR imager, aligned to the rotation axis of the telescope. Case 2: the target is not well centered: the fine centering checkout observations will be performed after a pre-offset estimated from the average positioning error.	1. Monitors the execution of the automated observing sequences for Case 1. Inform the observer and coordinate/confirm the re-centering actions for Case 2.	1. The NGAO system identifies the source(s) used for fine centering from the observer star list information.
Observations on-source science fields		
1. Load the observing sequences. Turn off the field rotator. If applicable: set off-axis LOWFS to track rotation of field.	1. Monitors the execution of the observing sequences	1. NGAO system (including instrument) provide the tools to load, execute and monitor the progress for the observing sequences. This includes providing an estimate of the maximum acceptable exposure time for the given observing wavelength/ detector scale such that an object at 1”, 2”, and 5” will not be blurred due to field rotation.
2. Monitors the execution of the observing sequences.	2. Monitors system performance variables such as LOWFS photometry	

	and AO performance.	
3. Monitors the image quality as frames are being recorded and display. TBD: requirements for the on-the-fly DRP.	3. Monitors NGAO health and fault detector.	
Calibrations: photometry		
1. Performs the necessary calibrations required by the data reduction pipeline.	1. Provides support for the required calibrations.	1. Provides documentation, characterization, and support for the required calibrations.
2. Load and execute the observing sequence for the photometric calibrations.		
Calibrations: PSF		
1. Repeat observing sequence on one or more analogous stars (identical guidestar magnitude(s), zenith angle).	1. Provides support for the required calibrations	1. Provides documentaion, characterization, and support for the required calibrations.
2. Calibrate the PSF possibly using PSF reconstruction based on ancillary telemetry (WFC and Cn^2 data).		2. The NGAO system records ancillary data throughout observations and provide the tool for reconstructing the PSF.

Table 17: Observing tasks for NIR imaging in Fixed-Pupil mode

7.3.3 Post-observing tasks

See Section 6.7.

7.4 Gas Giant Planets

This science case will be described and discussed in KAON 6XX. The goals of this science case are mostly to study the atmosphere of the Giant planets and their close environment (dust ring, inner satellite). The satellites of the Giant Planets will be used as Tip-tilt references. Because of the glare of the planet disk in visible and near-infrared i) the TT reference needs be bright and far enough from the disk (estimated to ~3” from the limb for V=5 satellites ii) the LGS “3+1” asterism needs to be at 10-15” from the limb. The best image quality should be obtained when the i) satellites are co-moving to allow long integration time (~2-5 s) ii) satellites are located on both side of the planet to better correct from the anisoplanetic effect iii) the LGS 3+1 asterism is located nearby the science target.
This is definitely one of the most challenging science observations since the target and the TT references have their own proper motions. However, because of the large numbers of satellites (~40 for Jupiter, ~60 for Saturn) with brightness in visible varying from 5 to 22 mgnitude, there is a large number of possible configurations. Consequently, this science case should be able to be performed for a wide variety of designs for the NGAO system.

7.4.1 Pre-observing tasks

See Section 6.6.

7.4.2 Observing tasks

Astronomer	Support staff	Instrument
Target selection		
1. The astronomer selects the next science target (Jupiter or Saturn) among the planned observations. The astronomer checks the target field status for observation planning: target field uptime, laser traffic control clearance during the anticipated observing time, etc.	1. The support staff checks the science field observability status: target field uptime, target submitted to LCH, LCH no-propagation windows, laser traffic control clearance, etc.	1. A tool provides information and status on observability using LGS for the science targets. The tool displays: telescope limits and target uptime, target LCH status, laser traffic control status on target, etc.
Field identification		
1. The astronomer prepares the necessary information to review and ID	1. Command telescope slew and request setup for NGAO (acquisition, laser,	1. Given selection of instrument, number and coordinates of science

the field in the R wavelength range: R-band chart showeing the configuration of the planetary system (with satellites), relative coordinates with respect to the center of the planet (X & Y) and their proper motions.	AO, pick-off alignment, instrument) based on observing sequences information.	targets and TT satellites, pick-off alignment information, the tool output a configuration for NGAO sub-systems (acquisition, laser, AO, etc). This tool can run in a preview mode in the afternoon during observing checkup. Execute setup commands for NGAO (acquisition, laser, AO, pick-off alignment, instrument) based on observing sequences information.
2. Once the telescope is pointing at the science field and the field rotated as requested, the astronomer helps ID the field using the acquisition camera display, a catalog image of the same field and any additional information. Astronomers use the AO guide stars as a reference in the R-band.	2. Assesses whether the telescope pointing needs to be adjusted on a nearby reference star and define the location of the LGS asterism. Based on the AO guide stars, ID the field using the acquisition camera display, a catalog image of the same field and any help from the acquisition system and the astronomer.	2. The acquisition system displays simultaneously the on-sky recorded image, a catalog image of the field at the same wavelength, orientation and scale, and the coordinates and information for the AO guide stars. The tool attempts to cross-correlate the two fields and ID the brightest objects. The ID information for the brightest GS in the field is overlaid to the recorded image. The process will confirm by the telescope operator
Science fields and guide stars acquisition		
1. Review the science instrument setup.	1. Monitors the progress on the science fields acquisition by checking that the AO GS is registered with the location of the probe arms (e.g., counts on LOWFS). *Note that this is an off-axis acquisition where the pointing origin is re-defined for each new science field geometry (not currently implemented with Keck AO).*	1. The acquisition software (MAGIQ) estimates the telescope offset and applies this offset. The science field acquisition is performed by registering at least one AO GS with a pixel location on the acquisition camera (pointing origin) such that the science target(s) are registered with the pointing origins corresponding to the center of the science detector(s).
2. Monitor the AO performance during acquisition and wait for go-ahead from support staff and system!	2. Monitors the progress of NGAO acquisition. There should not be any manual acquisition step as it generally slows down efficiency and reliability. If the chosen configuration does not give good correction, a second one will be chosen. Gives the go-ahead to the astronomer when NGAO acquisition completes.	2. The NGAO software commands the LGS and LOWFS acquisition, closes the loops and optimizes the system performance. The software informs on "AO readiness" when NGAO acquisition is complete and performance is optimized.
Fine centering		
1. Centering by with an accuracy of 1 arcsec is good enough for this science case. No need for fine centering		
Observations on-source science fields		
1. Load the observing sequences	1. Monitors the execution of the observing sequences	1. NGAO system (including instrument) provide the tools to load, execute and monitor the progress for the observing sequences.
2. Monitors the execution of the observing sequences.	2. Monitors system performance variables such as LOWFS photometry and AO performance.	
	3. Monitors NGAO health and fault	

	detector.	
Dither on the science field		
1. Monitors the execution of the observing sequences. The dither pattern is defined in the observing sequences and the pattern cannot be changed on-the-fly. The pattern can be defined in sky or instrument coordinate systems for a given sky orientation.	1. Monitors the execution of the observing sequences	1. The NGAO system dithers the science targets around the science array with minimal overhead - by repositioning the science field pick-off only, for move if the pick-off FoV permits - or by repositioning all pick-off (case dither amplitude is larger than pick-off FoV) - See KAON 558
2. Monitors the image quality as frames are being recorded and display. TBD: requirements for the on-the-fly DRP.		
Calibrations: telluric and photometry		
1. Performs the necessary calibrations required by the data reduction pipeline.	1. Provides support for the required calibrations. The requirements for the flat-field and spectral calibrations required by the data reduction pipeline will be detailed during the study and design of the d-IFS.	1. Provides documentation, characterization and support for the required calibrations.
2. Load and execute the observing sequence for the telluric and photometric calibrations.		
3. Calibrate the PSF possibly using PSF reconstruction based on ancillary telemetry (WFC and Cn^2 data).		3. The NGAO system records ancillary data and provide the tool for reconstructing the PSF.

Table 18: Observing tasks for Vis/NIR imaging of Giant Planets

7.4.3 Post-observing tasks

See section 6.7.

7.5 Other Science Drivers

Here we summarize other science drivers whose observing scenarios will be similar to those outlined in detail above. Note that this is not an exhaustive list, but we believe that other potential science cases not listed here will be similar to these and the ones listed above, and will be able to follow similar observing procedures and sequences.

Table 19: Other Science Driver Observing Scenarios

Science Driver	Corresponding observing scenario(s)	Notes
QSO host galaxies	6.1 Galaxy Assembly and Star Formation History	May want to use coronagraph with imager.
Gravitational Lensing	6.1 Galaxy Assembly and Star Formation History	
Astrometry Science	6.3 Astrometric Measurements of General Relativity Effects in the Galactic Center	TT stars will not be as bright
Resolved Stellar Populations	6.3 Astrometric Measurements of General Relativity Effects in the Galactic Center	
Debris Disks and Young Stellar Objects	6.4 Imaging and Characterization of	Also, fixed pupil mode

	Extrasolar Planets around Nearby Stars	
Size, Shape, and Composition of Minor Planets	6.5 Multiplicity of Minor Planets	Also an IFU mode (binned to R~100)?
Characterization of Gas Giant Planets	7.4	
Characterization of Ice Giant Planets	7.4 or 7.2	
Backup (NGS) Science Titan and Io	7.2 NGS mode	

8 Use Cases

8.1 Observation Planning

8.1.1 Search and selection of AO natural guide stars

The NGAO Planning Tools will include a "catalogue search tool" which searches either local or remote databases for NGS around coordinates provided by the observer. Catalogues which could be used for guidestar search are detailed in KAON 567. This tool should provide essentially the same functionality as the current Keck 2 LGS AO Guidestar Tool, superimposing the LOWFS/TWFS patrol range on a map of the available guide stars, automatically selecting the best possible asterism, and providing an estimate of AO performance for a that asterism. The user should be given the option of changing the asterism as necessary to avoid interference between the pickoff arms and science target. When the user is satisfied with the NGS configuration, the coordinate offsets of the NGS associated with each science target should be saved to a guidestar file which will later be read by the OSC Tools for configuration of the AO system.

The guidestar file should be considered mandatory, in the sense that steering the LOWFS pickoffs to NGS manually is likely not an option. If the observer were to decided to change NGS asterisms during an observation, they will have to save a new guidestar file, and have the AO operator load it in the OSC Tools.

The observer will use the catalogue search tool at their home institutions to prepare proposals and target lists in advance, and in daytime at Keck HQ immediately before observing.

8.1.2 AO performance estimation

One aspect of the catalogue search tool described in the last section is to provide an estimate of AO performance based on the NGS guidestar configuration. This estimate must also include environmental factors such as the turbulence strength and wind speed, though default values can be used for initial guidestar selection. The performance estimate will used by the software to automatically select the optimal NGS asterism, and should be provided to the user.

8.1.3 Planning the observing sequences with "INST"

Once a list of science targets and NGS guidestars has been generated, observing sequences for each target must be planned. This includes defining filters, the individual integration times, number of integrations, any dithering on target, and offsets to sky, etc. Note that these include actions to be performed both by the AO system and internal to the instrument. A software tool should be provided to allow the complete observing sequence to be defined, for example using a simple scripting language to specify a sequence of commands. For efficiency, it must be possible to define commands to be executed in parallel, for example changing an instrument filter and dithering the object on the science focal plane. The observing sequence should be associated with one or more science targets, and save to a file to be loaded when that target is selected.

While carefully planned observing sequences can greatly increase observing efficiency, it will still be possible to manually perform all functions (eg. from an instrument GUI). The ability to define observing sequences should be available to observers at their home institutions, and at Keck HQ for daytime planning.

8.1.4 Planning the observing sequences with IF

TBD

8.1.5 Exposure time estimation with "INST"

A necessary input to planning observing sequences is an estimate of the SNR reached on a target of given magnitude and color in an exposure of a given length, or conversely the exposure time required to reach a given SNR. This estimate requires knowledge of the science target, the instrument configuration, and the NGS asterism and atmospheric parameters.

Used for an initial estimate of exposure time, the calculator should take as input the guidestar file, science target, instrument, and atmospheric parameters and output an estimated exposure time to achieve a given SNR. A more advanced mode might allow one to load in an observing sequence and compute the predicted SNR. As with the previous tools, this one is likely to be used both at observer's home institutions and in daytime at Keck HQ.

8.1.6 Observing efficiency estimation with "INST"

A tool should be provided to estimate open-shutter observing efficiency of an observing sequence. This function could be integrated into a GUI in which the sequences are built, or be provided by a stand-alone tool. Observers will use this tool to optimize the efficiency of their sequences.

8.1.7 Output of the planning process

For maximum efficiency, the observer should start the night with the following files saved.
- Target list
- Guidestar file: Associates relative offsets of NGS guidestars with each target in the target list
- Observing sequence file: Associates an observing sequence with each target in the target list

8.2 LGS-AO Acquisition

Table 20 breaks the LGS-AO acquisition process into 8 phases, and indicates some of the activities that can be performed in parallel. The following 7 subsections detail these phases, and assign reference numbers to the individual acquisition steps, most of which will be commands or sequences of commands issued by the Multi-System Command Sequencer (MCS).

Table 20: Overview of the LGS-AO acquisition sequence

Step	Phase	Parallel Steps
0	Select next target	Integrating on current target
1	Terminate previous observation	
2	Configure AO for acquisition of the next target	Telescope slew to next target; configure science instrument
3	Center the telescope on the science target	Configure laser asterism & LOWFS/TWFS
4	Acquire LGS guidestars	Configure LOWFS/TWFS
5	Acquire NGS guidestars	
6	Close remaining control loops	Acquire initial science image to check pointing, integration
7	Optimize servo control loops	Science integration begins

8.2.1 Terminate previous observation

The next target will be selected while integrating on the previous object. The observer will use the NGAO Planning Tools to select the next target, whose coordinates and offsets to the NGS will be sent to the OSC Tools. The following factors will be taken into account by the observer, and should be available in the Planning Tools:
- Science priority (as defined by the observer)
- Zenith angle / airmass.
- Potential Laser Traffic Control System conflicts.
- Observing conditions (r_0, transparency)

The night assistant will terminate AO correction on the current target using the OSC tools. A single command should perform the following sequence of steps, coordinated by the MCS.
1. Open all servo control loops.
2. Load optimal static shapes onto all deformable mirrors.
3. Shutter the lasers.

The night assistant will then initiate the slew to the next target.

8.2.2 Configure AO for acquisition of the next target

While the telescope slews to the pointing star for the next target, the night assistant will use the OSC Tools to configure the AO system for acquisition of the next target. The MCS will coordinate the following steps, which can all be performed simultaneously:
4. Install the acquisition camera fold mirror
5. Center all tip/tilt mirrors.
6. Configure the acquisition camera (integration time, binning, etc.)
7. Tune lasers off of the 589 nm wavelength sodium resonance.

8. Move the Patrolling LGS asterism generator to correspond to the relative coordinate offsets between the NGS and the science target.
9. Move the Patrolling LGS WFS pickoff arms to focal plane locations corresponding to the relative coordinate offsets between the NGS and the science target, and focus conjugate to the expected sodium layer range.
10. Move the LOWFS/TWFS pickoff arms to correspond to the relative coordinate offsets between the NGS (up to 3) and the science target.
11. Configure all servo loop parameters (wavefront sensor frame rates, servo gains, reconstructors, etc.) based on guidestar properties and atmospheric conditions.

For optimum efficiency, installation of the acquisition fold mirror, centering of the first relay tip/tilt mirror, and configuration of the acquisition camera should be completed by the end of slew. Moves of the PnS asterism generator and PnS WFS should be completed before offset to the science target is complete. Moves of the LOWFS/TWFS pickoff arms should be completed by end of the LGS acquisition sequence.

The main contributions to the relative centering error of the LOWFS/TWFS pickoff arms to the science target are the following:

- The accuracy for the knowledge of the separation distance and PA between the stars and the galaxies from the literature. This information is provided by the astronomer, and can be less than 10 milli-arcsecond if the field has been observed (recently) with HST cameras. The USNO-B on-line catalog provides an astrometric accuracy of 200 milli-arcsecond, and the astrometric solution for the USNO-B, GSC-II and SDSS catalogs are improved as the proper motions are being calibrated using GSC-I (KAON 467).
- The accuracy in positioning the pickoff arm for each science target w/ respect to the TT closed-loop reference position for the LOWFS, which is the total of:
    - The internal positioning accuracy and position stability for each individual pick-off arm (science and LOWFS) – the requirement is less than 5 milli-arcsecond (KAON 548)
    - Registration accuracy and stability between LOWFS and science arms including TT stage positioning accuracy.
- The differential atmospheric refraction between the LOWFS and the science.
- The total contribution from the optical distortions due to thermal gradient, alignment error, woofer and MEMs positioning between the science array and the LOWFS.

KAON 559 provides a conceptual study report for the "Interim LOWFS and LGS Object Selection Mechanism" and shows that the requirement for the positioning accuracy can be met (contribution #2 above). However, the last two contributions will need further analysis.

8.2.3 Center the telescope on the science target

Pointing errors of tens of arcseconds are possible after long slews with the Keck telescopes. The acquisition sequence must therefore include a pointing correction step, based on the known location of a star near the science target. Use of a bright pointing star allows the process to proceed rapidly using automated routines, rather than relying on human operators to identify faint asterisms in the field of the science target. We therefore baseline the following procedure, which the night assistant will initiate and control using the OSC Tools:

12. Slew to a V~10 SAO star near the science target (within ~1 degree).
13. Record an acquisition camera image.
14. Correlate the location of the brightest object(s) with catalogued bright stars (eg. SAO catalogue), to determine the required offset to center the chosen star on the science instrument pointing reference.
15. After verification by the night assistant that the computed offset is reasonable, command the telescope to offset to center the star on the pointing reference.
16. Record an acquisition camera image to verify the new pointing. If necessary, repeat the process.
17. Offset the telescope to the coordinates of the science target.
18. Remove the acquisition camera fold mirror.

8.2.4 Acquire LGS guidestars

The guidestar acquisition sequence begins acquisition of the LGS, so that NGS acquisition can benefit from high-order wavefront correction. The LGS acquisition sequence will be fully automated (with the exception of any required spotter verification of laser projection), and initiated by the night assistant using the OSC Tools. The sequence of steps is a follows:

19. Verify that conditions are acceptable for laser projection. This currently relies on radio communication with the spotters.

20. Project the LGS asterism. The laser has previously been tuned off of the 589 nm line, and PnS asterism generator and WFS configured to match the NGS guidestar locations, in step 2 above.
21. Record the WFS background signal for all LGS WFS.
22. Tune lasers back onto 589 nm sodium resonance.
23. Check signal levels on the LGS WFS, which might be low if there is inaccurate relative positioning between the launch mechanisms (PnS and asterism) and WFS. If any LGS WFS are below threshold, initiate a trouble-shooting tree, which could include a search pattern with the relevant LGS asterism generator stage, WFS tip/tilt mirror, or PnS WFS pickoff arm until the LGS is located.
24. Close the LGS WFS tip/tilt loops (3 independent servo loops for the PnS LGS, one for the tomography LGS, controlling the tip/tilt mirrors in the LGS WFS assembly).
25. If any LGS tip/tilt mirror is near it limit, offset the relevant LGS WFS pickoff arms (or PnS asterism generator stage – TBD which is the appropriate one) to re-center the tip/tilt mirror.
26. Close the woofer high-order servo loop (tomographic reconstruction of the woofer DM commands based on the tomography lasers).
27. Close the PnS high-order servo loops (3 independent servo loops controlling DMs in the LOWFS pickoff arms).

8.2.5 Acquire the NGS guidestars

The NGS guidestar acquisition sequence will be fully automated, initiated by the night assistant using the OSC Tools. We assume here that 3 NGS are available. All three LOWFS have a 5 arcsecond field of view. One measures tip/tilt, focus, and astigmatism (TTFA-WFS), while the other two measure only tip/tilt (TT-WFS). The LOWFS pickoff arms are configured such that the light of the brightest NGS falls on the TTFA-WFS. The sequence of steps is as follows:

28. Record long exposure (~1-5 s, TBD) full-frame images with the TTFA-WFS, which should be pointed at the brightest NGS. The NGS will at this stage have a diffraction-limited core, broadened by static focus error and jittering around with atmospheric tip/tilt.
29. Offset the TTFA-WFS pickoff arm to center the NGS in its field of view.
30. Select the region of interest over which to read the TTFA-WFS detector (may always default to the same low-noise/central pixels), and optimum framer rate base on measured star flux.
31. Offset the TTFA-WFS pickoff arm a small distance (1-5”) to blank sky.
32. Record the TTFA-WFS background signal, over only the region of interest and at the operating framerate.
33. Offset the TTFA-WFS pickoff arm back to the brightest NGS.
34. Close the TTFA-WFS tip/tilt loop (control the tip/tilt mirror in the sensor’s pickoff arm, based on the TTFA-WFS tip/tilt signal).
35. Close the woofer tip/tilt loop (control woofer tip/tilt stage, based on a weighted mean of the three LOWFS tip/tilt mirror positions.) Since only TTFA-WFS tip/tilt loop is closed at this stage, the woofer tip/tilt stage will effectively take over control, leaving the TTFA-WFS stage centered. However, the system is now configured to operate normally when the remaining two LOWFS tip/tilt loops are closed.
36. Close the focus control loop (control the focus of all LGS-WFS, based on the TTFA-WFS focus measurement).
37. Record long-exposure (~1-5 s, TBD) full-frame images with the TTWFS. All NGS will at this stage be diffraction-limited and be jittering only by the differential tip/tilt due to their angular separation (order ~10 milliarcseconds).
38. Offset each TT-WFS pickoff arms to center the NGS in the sensor’s field of view.
39. Select the region of interest over which to read each TT-WFS detector (may always default to the same low-noise/central pixels), and optimum framerate based on measured star flux.
40. Offset the TT-WFS pickoff arms a small distance (1-5”) to blank sky.
41. Record the TT-WFS background signal, over only the region of interest and at the operating framerate.
42. Offset the TT-WFS pickoff arms back to the NGS.
43. Close the TT-WFS tip/tilt loops (2 independent servo loops, controlling the tip/tilt mirrors in the respective sensor’s pickoff arms). The woofer tip/tilt stage will now reflect the weighted mean of all three LOWFS tip/tilt mirror positions, and the individual LOWFS tip/tilt mirrors will only correct the differential tip/tilt signal.

8.2.6 Close remaining control loops

Once all guidestars have been acquired and guidestar servo loops (LGS TT, LGS PnS HO, NGS TT, NGS focus, Woofer TT) are stable, the night assistant will use the OSC Tools to close the science channel servo control loops:

44. Close the tweeter high-order servo loop (split the high-order tomographic control between the woofer and tweeter).
45. Close the TWFS servo loop (control the HOWFS centroid offsets or other input to the tomography computation, based on the TWFS and possibly also the TTFA-WFS astigmatism signal).

8.2.7 Optimize the servo control loops

When all servo control loops have been closed, initial integrations with the science instrument can begin, to check pointing, integration times, etc. However, servo loop optimization will proceed during this time. Specifically, the AO operator will run an AO performance analysis tool which uses system telemetry to compute actual and optimal loop bandwidths. Changes in servo loop gains can be made without interrupting science integrations. However, optimization may require changing the frame rates of either LGS or NGS wavefront sensors, which could require interrupting science observations.

A change in the frame rate of the LGS WFS is unlikely to be required unless laser power or atmospheric conditions have significantly changed. However, if necessary, this optimization would require the astronomer to terminate their observing sequence. The following automated procedure would be performed, initiated by the night assistant using the OSC Tools:

1. Open all servo loops.
2. Tune lasers off of the 589 nm wavelength sodium resonance.
3. Change the laser WFS frame rate as required.
4. Record the WFS background signal for all LGS WFS.
5. Tune lasers back onto 589 nm sodium resonance.
6. Close all servo loops in the same order as listed in sections 8.2.4 - 8.2.6.

Science observations do not need to be interrupted for a change in frame rate of an NGS WFS. The following steps illustrate the procedure for the TTFA-WFS. If more than one sensor needs a change in frame rate, then they would be done sequentially to allow the system to continue to operate in closed loop.

1. Open the focus control loop (cease controlling the focus of the LGS WFS.)
2. Open the TTFA-WFS tip/tilt loop (cease controlling the tip/tilt mirror in the TTFA-WFS pick-off arm.)
3. Offset the TTFA-WFS pickoff arm a small distance (1-5”) to blank sky.
4. Change the TTFA-WFS frame rate as required.
5. Record the TTFA-WFS background signal, over only the region of interest and at the operating frame rate.
6. Offset the TTFA-WFS pickoff arm back to the NGS.
7. Close the TTFA-WFS tip/tilt loop.
8. Close the focus control loop.

Throughout this procedure, the woofer tip/tilt mirror will continue to be controlled using the remaining NGS, with some degradation in tip/tilt performance.

8.3 NGS-AO acquisition

The NGS-AO acquisition process is far simpler, requiring only the acquisition of a single NGS guidestar. Table 21 breaks the process down into 7 phases, several of which (steps 0-1, 3) are identical to LGS-AO acquisition (see Section 8.2 for details). Phases 2 and 4-6 are described in further detail below.

Table 21: Overview of the NGS-AO acquisition sequence

Step	Phase	Parallel Steps
0	Select next target	Integrating on current target
1	Terminate previous observation	
2	Configure AO for acquisition of the next target	Telescope slew to next target; configure science instrument
3	Center the telescope on the science target	Configure NGS-WFS
4	Acquire NGS guidestar	
5	Close control loops	Acquire initial science image to check pointing, integration
6	Optimize servo control loops	Science integration begins

8.3.1 Configure AO for acquisition of the next target

While the telescope slews to the pointing star for the next target, the night assistant will use the OSC Tools to configure the AO system for acquisition of the next target. The MCS will coordinate the following steps, which can all be performed simultaneously:

1. Install the acquisition camera fold mirror
2. Center the woofer and tweeter tip/tilt mirrors.
3. Configure the acquisition camera (integration time, binning, etc.)
4. Move the NGS-WFS field steering mirrors to match the offset of the NGS from the science target.
5. Configure all servo loop parameters (wavefront sensor frame rate, pupil sampling, servo gains, reconstructors, etc.) based on guidestar properties and atmospheric conditions.

8.3.2 Acquire the NGS guidestar

Following centering the telescope on the science target, the science target should be located on the instrument pointing origin to within ~1 arcsecond. The following automated NGS guidestar acquisition sequence will then be initiated by the night assistant using the OSC Tools:

6. Offset the tweeter tip/tilt mirror a small distance (~5") to direct blank sky onto the NGS-WFS.
7. Record the NGS-WFS background signal.
8. Offset the tweeter tip/tilt mirror back to center the guidestar on the NGS-WFS.
9. Verify that sufficient signal is present on the NGS-WFS. If below threshold, initiate a trouble-shooting tree, which could include imaging the science field with the acquisition or science cameras, and/or a search pattern with the NGS-WFS field steering mirrors.

8.3.3 Close control loops

The following automated NGS sequence will then be initiated by the night assistant using the OSC Tools:

10. Close the woofer tip/tilt control loop (control the woofer tip/tilt stage based on NGS-WFS tip/tilt signal).
11. Close the woofer high-order control loop (control the woofer based on NGS-WFS signal).
12. Close the tweeter high-order servo loop (split the high-order control between the woofer and tweeter).

8.3.4 Optimize the servo control loops

Once servo control loops have been closed, initial integrations with the science instrument can begin while servo loop optimization proceeds. The AO operator will run an AO performance analysis tool which uses system telemetry to compute actual and optimal loop bandwidths. Changes in servo loop gains can be made without interrupting science integrations. Any necessary change in the NGS-WFS framerate will require interrupting science observations. The procedure would be as follows:

13. Open all servo loops.
14. Offset the tweeter tip/tilt mirror a small distance (~5") to direct blank sky onto the NGS-WFS.
15. Change the NGS-WFS framerate as required.
16. Record the NGS-WFS background signal.
17. Offset the tweeter tip/tilt mirror back to center the guidestar on the NGS-WFS.
18. Close all servo loops in the same order as listed in sections 8.3.3.

8.4 Observing sequences execution

The observing sequences will be coordinated at the Observing Sequence Tool level to minimize the overhead during dither and offset scripts: as soon as the instrument reports that the readout is complete, the OS tool will command the dither or offset either in instrument pixel or sky coordinates [Why wait until readout is complete? How about moving once readout starts?]. KAON 558 proposes possible scenarios for dither and offset. We anticipate that any repositioning of the observing reference frame of less than 5" (TBC) will be performed by repositioning internal optics and will not require to move the telescope (hence not require to open any loops). These we propose to define as "dither" and should take less than 5 seconds.

Conversely, any move that require to move the telescope and open the AO loops are defined as offset, and may require longer overhead (~ 15 -30 sec - TBC).

8.4.1 Initiating an observing sequence in NGS mode

An observing sequence could be defined as a combination of dither, offset, and filter sequences. Assume that AO loops are closed and system is optimized. For survey programs that use the same setup repeatedly, there should be an option to disable instrument configuration checks (filter, readout mode, etc). Otherwise, instrument configuration should be sent to the instrument.

8.4.2 Initiating an observing sequence in LGS mode

Should be the same as 8.4.1 Initiating an observing sequence in NGS mode.

8.4.3 Dither sequences with the narrow field science instrument

- Observer loads observing sequence file that includes instrument configuration and dither pattern similar to OSIRIS ddf files
- Observer has option to disable instrument configuration checks to speed survey work in a single setup
- Observer starts the observing sequence
- Instrument is configured

- Exposure(s) start
- When exposure(s) in this position are done, instrument sends signal to Master sequencer. Final readout starts
- TTM2 moves slightly to dither the science field while keeping AO loops closed.
- After a settle time (TBD) and verifying that readout is complete and detector is ready, next exposure(s) start
- Once all positions are complete, TTM2 returns to starting position.

Observing sequence can piece together several dither sequences in series if observer wishes to use more than one filter. In these cases, TTM2 would return to the starting position only after all dither sequences are completed.

8.4.4 Dither sequences in NGS AO

Should be the same as 8.4.4 Dither sequences with the narrow field science instrument

8.4.5 Offset sequences with the narrow field science instruments

Offsets are necessary when the science target is extended or within a crowded field such that small dithers are insufficient to record a reasonable sky frame. Offsets may occur before a dither sequence, during a dither sequence, or after a dither sequence as part of an observing sequence.

- Observer loads observing sequence file that includes instrument configuration and dither pattern similar to OSIRIS ddf files
- Observer has option to disable instrument configuration checks to speed survey work in a single setup
- Observer starts the observing sequence
- Dither sequence occurs
- Once the image readout starts, a signal is sent to the master sequencer.
- Master sequencer puts image acquisition on hold, opens loops, sends telescope and probe arm moves in parallel.
- Assume AO bench moves will be faster than telescope moves
- Once telescope move is complete, master sequencer verifies light on WFSs and recloses loops.
- Image acquisition resumes.

One can imagine an offset that moves the TT stars into a vignetted region. In these cases…

8.4.6 Offset sequences in NGS AO

Should be the same as 8.4.7 Offset sequences with the narrow field science instruments

8.4.7 Filter sequences with the science instrument

Filter sequences should be considered part of the dither/observing sequence. One should run through a dither sequence with the same instrument setup, then change filters to reduce the overhead associated with changing filters and to ensure sky frames are taken close in time to science frames.

8.5 Calibration observing sequences

Calibrations need to be defined. Night-time cals should only be PSF, telluric, and photometric cals. Wavelength solution should not change very often unless IFS design is radically different than OSIRIS.

8.5.1 PSF sequences

Observer may need to have a point source defined with a similar TT star asterism. One would observe the PSF object much like a science object (same dither sequence) such that the PSF object has the same offsets from the TT objects as the science object did.

8.5.2 Telluric and photometric standard sequences

Telluric standard sequences should be very similar to NGS AO dither sequences. Photometric standard sequences will be similar, but perhaps without DM loops closed.

8.5.3 Background emission sequences

With IR detectors for the LOWFS, we anticipate the need to update sky backgrounds while observing. We may also need new laser WFS backgrounds; however, we likely cannot do these while integrating.

While observing, it should be possible to quickly offset one LOWFS probe arm and record a new sky background while the other two remain on target and closed loop. As the point-and-shoot lasers are all the same laser, it will not be possible to individually tune each LOWFS's LGS off of the sodium wavelength while the other two remain on the sodium wavelength.

LOWFS Backgrounds:

- If TTFA/TWFS LOWFS, wait until TWFS exposure complete.
- Pause TWFS image acquisition.
- Open LOWFS TT loop.
- Offset LOWFS probe arm by some distance (of order an FOV).
- Record a background.
- Return LOWFS probe arm from offset.
- If light on LOWFS, close loops.

LGS WFS Backgrounds:
This could be part of an observing sequence.

- After data acquisition is complete, open LGS loops.
- Detune laser from sodium wavelength.
- Record background.
- Retune lasers.
- Reclose loops.

8.5.4 Twilight sequences

This probably means evening twilight. Current LGS system does an on-sky checkout in NGS and LGS modes, as well as a laser alignment at zenith. NGAO will probably also require an on-sky checkout of these systems.

8.6 Switching AO modes and science instruments

8.6.1 From wide to narrow field science

The only switch will be from imager to IFS or vice versa. These will be the same instrument and an internal optic will allow access to either detector.

8.6.2 Switching AO modes

IF/NGAO switch.

8.6.3 Switching to backup instrument

- Open loops and shutter lasers.
- Run end of night script for AO system.
- Select backup instrument from DCSGUI and wait for tertiary move to complete.
- Load backup starlist and slew to area of first target.
- Bring up software for backup instrument.
- Focus telescope.
- Begin observing with backup instrument.

8.7 Troubleshooting common observing situations

8.7.1 No light on NGS sensors (acquisition)

In NGS mode, acquisition should not start if there is no light on the NGS WFS. This space is meant for no light on LOWFS during LGS acquisition. Assuming the LGS system is functioning normally, one must determine if there is no light on only one sensor or more than one.

If only one LOWFS is without light, close loops on the other two and then perform a small spiral search with the third probe arm. It is possible that this object was a plate defect or catalog error; in this case one must find another star for the LOWFS.

If more than one LOWFS has no light, one must consider a pointing problem or stage problem. First, verify that all stages are at their required locations, then re-verify pointing using the acquisition images recorded before LGS propagation.

8.7.2 No light on LGS sensors (acquisition)

8.7.3 Variable counts on NGS sensors

Variable counts on an NGS sensor can be caused by several factors. Among causes attributable to conditions, these are clouds, poor seeing, and windshake. In perfect observing conditions, variable counts could be the result of a stale WFS background, a TT mirror or LOWFS probe arm malfunctioning or unpowered, or a software issue such as low loop gains, an open control loop, or an incorrect mode setting.

External conditions can be double checked with other monitors. Clouds will cause variable counts on all NGS and LGS WFSs. They will also be visible on an all-sky camera or to a trained eye. Poor seeing can be diagnosed via the MASS/DIMM or seeing monitors on other telescopes. Windshake can be seen in the servo errors of the telescope. Operators will require tools that alert them to the variable counts condition and then let them easily check these external conditions easily. Software designers should take care in the design of the alerts such that the alerts can be silenced or acknowledged and not become an annoyance.

Internal conditions leading to variable counts can be harder to diagnose. Sanity checks such as closed loops and standard configurations should be checked (e.g., LGS mode, but NGS beamsplitter deployed) as well as the time since the last background was recorded for the offending WFS should be noted. Operators should have access to a checklist of settings and conditions to check when variable counts are detected.

8.7.4 Variable counts on LGS sensor

In addition to the conditions listed that may cause variable counts on an NGS sensor, there are additional causes of count variation on LGS sensors. Among these additional causes are natural sodium layer variations and laser intensity variations. If the laser intensity is changing, this may indicate a serious problem with the laser; coolant flow and temperatures should be checked to ensure proper operation. Generally, clouds and stale WFS backgrounds are the most common causes. External monitors or the presence of NGS variations can help diagnose clouds. Stale WFS backgrounds may be the cause if the moon or other bright source is nearby.

8.7.5 Laser interrupt from LTCS (including LCH)

Laser interruptions should be handled automatically by software:

- Predict upcoming collisions (telescope and satellite)
- Audio warning for pending collisions
- Loops open automatically
- Laser shutters automatically
- Visual alert when closure condition is cleared
- Re-request permission to propagate
- Propagate the laser
- Re-close loops

8.7.6 Observing interrupt for sub-system fault (AO, Laser, instrument, DCS, etc)

If any fault is detected that prevents keeping the lasers or stars on their respective WFSs, the control loops should automatically open such that the system is not correcting on noise. This can drive stages to limits or ruin alignments.

8.7.7 Etc

8.8 Post-observing

8.8.1 Data products

8.8.1.1 Science data product

8.8.1.2 AO & ancillary data product

8.8.2 Data storage and archive

8.8.3 PSF reconstruction

8.9 AO/Laser calibrations & alignment sequences

8.9.1 Day time calibrations

8.9.2 Night time calibrations

9 Observing support effort and technical operations

We summarize in this section the observing support effort and daily technical operations that will be needed to successfully prepare the NGAO/LGS and its instruments for the observation, and also to monitor and to improve its performance. This section is written based on discussions with the current Keck AO operation team, plus inputs from other observatories.

The OOCD goal is to describe how the features and functions of the design impact the observations described in the science cases. Even if this document is not intended to cover calibration of the AO system, the observing support effort and technical operations need to be described to give a flavor of their impacts on the operation and design of the instrument.

9.1 Science instrument support

The goal of the science instrument support is to:
- check if the instruments are working nominally
- calibrate the instrument
- perform routine maintenance
- solve issues related to night log tickets
- replace obsolete systems
- solve chronic problems
- implement requests from observers
- improve and optimize performance

9.1.1 Maintenance and calibration

The science instrument support is mostly done remotely from Waimea in coordination with summit activities. With the current Keck AO system physical access to the science instruments (NIRC2 and OSIRIS) is needed rarely)2-3 times per months), except for when an instrument is brought in or out of the AO enclosure.

A stable calibration plan could consist of the following tasks for each instrument:
- Image sharpening
- Check pointing
- Dark, flats, arc lamps, RON test
- Check performance monitoring flat-field structure, zero-points, sensitivity, throughput, noise from data taken during the previous night
- Specific calibration for IFS includes mapping the field elements to the spectral footprint by means of a scanning process. This produces the rectification matrices needed for the DRP. Although needed very infrequently, this a very involved process that needs significant amount of instrument and bench time, on the order of 100 hours.

Performance monitoring will include analyzing the data collected by the users. A criterion of quality for the night (cloudy, clear, photometric) based on the zero-point calculations could be delivered to the users. An estimate of the noise on the collected data could provide information on the sensitivity of the instrument, which varies with the OH glow, sky background temperature, and AO+instrument temperature. The first three sequences of tasks are needed to optimize the quality for the following night and detect any anomalies.

9.2 NGAO system operational support

The NGAO system will require additional operation support in comparison to the science instruments. For instance, the current LGS at Keck Observatory needs 2 FTE to be prepared for the night.

The goal of the NGAO support is to:
- check if the AO system is working nominally
- calibrate the system
- perform routine maintenance
- solve issues related to night log tickets
- replace obsolete systems

- solve chronic problems
- implement requests from observers
- optimize performance

9.2.1 Maintenance and calibration

The AO/LGS support is mostly done remotely from Waimea in coordination with summit activities. With the current Keck AO system access to the AO bench is needed 2-3 times per month.

A stable calibration plan for the AO system could consist on the following tasks:

- Dark, flats, RON test on each wavefront sensor (2 x TT NGS in near-infrared, 7 x LGS in visible, 1 x TTFA in visible)
- Check performance monitoring FWHM, sensitivity, throughput, noise from data of the TT NGS WFS taken during the previous night
- Check performance monitoring flux, size and focus from data taken with LGS WFS during the previous night

The last two sequences will be done automatically using the saved NGAO configuration prepared by the observers. An anomaly such as high background, low flux, extended spot could be used to identify a lower quality than expected. Monitoring of the background noise and RON on the wavefront sensors is needed to detect an anomaly on the WFS.

9.3 Before an observation night

In this section, we envision how an observing run is prepared and conducted by the Support Astronomer. The support astronomer is in charge of making sure that the telescope, AO systems and instruments will be ready for the science scheduled during the night.

After revising the proposal(s), the SA contacts the PI two weeks before their run to get a final target list. He schedules a meeting with the PI(s) and observer(s) to discuss instrument issues and their observing program. A final list of targets and their observing configuration should be finalized 4 days before the run. The support astronomer checks the list of targets and the observing configuration before submitting it to space command center (SCC).

For laser propagation safety, the support astronomer will need to contact various entities:

- Send to SCC at least 3 days before the run the final target list. 24h before the run, the SCC will provide windows of propagation that will be inserted in the control software.
- Contact FAA to send them the schedule of LGS propagation during the night (afternoon) and coordinate the spotter schedules.
- Send schedule of LGS propagation to “Mauna Kea” military base, which may in return request avoiding a specific area of the sky.
- Contact other observatories to broadcast LGS run and activate the Laser Traffic Control System (LTCS).

The windows of propagation in time and location from SCC and Mauna Kea military base should be inserted in the telescope control software to avoid conflicts automatically. The software should automatically check clearance for pointing and activating the lasers. The user and the telescope operator will be warned when the window of propagation is getting short (e.g., less than ~1h?) using a real-time graphical display and audio alarms at 60 sec prior to closure.

Currently the support astronomer stays most of the AO night.

10 Glossary

10.1 Acronyms and abbreviations

The following acronyms and abbreviations were used in this document:

- AGN: Active Galactic Nucleus
- AO: Adaptive Optics (do you really need to know that?)
- BH: Black Hole
- d-IFS: deployable Integral Field Spectrograph
- DM: Deformable Mirror
- DSS: Digital Sky Survey
- FoV: Field of View
- FWHM: Full Width at Half Maximum

- GS: Guide Star
- GUI: Graphical User Interface
- IFU: Integral Field Unit
- KAON: Keck Adaptive Optics Note, available from the NGAO Twiki site or from KeckShare
- LCH: Laser Clearing House
- LGS: Laser Guide Star
- LOWFS: Low Order Wavefront Sensor, sensors looking at a NGS used for tip-tilt / focus and astigmatism.
- LTCS: Laser Traffic Control System
- MAGIQ: Acronym for acquisition software
- NGS: Natural Guide Star used for sensing low and high order modes, depending on brightness and AO mode.
- NIR: Near Infra-Red
- PA: Position Angle
- PI: Principal Investigator
- PSF: Point Spread Function
- rms: root mean square
- SA: Support Astronomer
- TAC: Time Allocation Committee
- TBD: To Be Determined
- TT: Tip-Tilt
- TWFS: Truth Wavefront Sensor, sensor looking at a NGS used for providing a true reference for the average residual aberrations.

10.2 Jargon and definitions

The following terms were used with the corresponding definitions:

- Dither:
- Offset:

11 Appendix: Galaxy Assembly and Star Formation History with a d-IFS

This science case was moved to an appendix since it was written prior to the decision to descope the d-IFS. It is kept here for possible future reference.

The NGAO Science Case on Galaxy Assembly and Star Formation History is one of the five Key Science Drivers, which place the most restrictive or technologically challenging constraints on the NGAO system. The requirements for this science case are described in Section 2.1.1 in KAON 455. The following sub-sections document its example observations.

11.1 Description

The observing goal for this science case is to survey more than 200 galaxies over a few years (*reqt #1.2*). This is possible by using a deployable NIR spectrograph over a field of ~ 2 arcmin diameter. The number of targets per field of regard depends on the number density for the class of objects being studied and varies between 0.1 to 40 arcmin^{-2} (see KAON 455, table 3). Depending on the object brightness, the NGAO + dIFS will dedicate ~ 1.5 to 4 hours of open shutter time on a set of targets (*reqt #1.2*).

Parameters	Value / Method	Comments
Science instrument	d-IFS	
Instrument setup	IFU FoV: 1 x 3 arcsec J-K wavelength range 70 mas/spaxel 35 mas/pixel TBD	
Total integration time on target	1.5 - 4 hours	*reqt #1.2*
Individual integration time on target	15 - 30 min	
Individual integration time on calibration stars	20 - 60 sec	
Positioning precision of IFU with respect to the	< 100 milli-arcsec	goal of 20 milli-arcsec ? between LOWFS arms and IFU

NGS		arms?
Background estimation	Dither on IFU	Observer are likely to use a dithering script on the IFU
	One IFU as dedicated sky	One possibility is to use 1 IFU arm as a dedicated sky for all IFU units, but it is unclear if the IFU units can be calibrated well enough to each other to enable this.
	Dedicated background by offsetting the IFU at least once	
Instrumental calibration	Using arc lamps and integrating sphere	Performed during the day
PSF calibration	Using an IFU ?	Telemetry-based PSF reconstruction
Telluric standard	Using an IFU ? Dedicated observing sequence	

Table 22: Summary of the observing parameters for the "galaxy assembly and star formation history" science case

11.1.1 Assumptions and prerequisites

In estimating the observing efficiency, we have made the following assumptions:

- In parallel to observing a set of extragalactic targets, we anticipate the observer will dedicate one of the deployable units on a point-like source to calibrate for the PSF, and possibly for the telluric absorption (depending on the spectral class for the point-like source). This point-like source will also be used to monitor the centering of the field.
- Yet, for every set of targets, we anticipate the observer will calibrate for the telluric absorption after the science spectroscopy observations and within a certain interval in air mass and time. This should add approximately 10 min of observing time to the observations of the set of targets. In addition, we anticipate the observer will want to calibrate the flux by observing flux standards, twice through the night, and possibly including during twilight.
- We assumed individual integration time between 15 and 30 min on the d-IFS for the science targets and between 1 and 3 min for the standards. (*70 mas spaxels at K-band may require shorter integrations, perhaps 5 min.*)
- For an observation on a set of targets, we find that it will take 12 min on average for the full setup from initiating the telescope slew till first start of science-quality exposure. The open shutter time will be 155 min on average with 3 min of overheads for dither/readout and 5.3 min for re-centering. The observation of the telluric of flux standard will take approximately 9 min including ~ 55% total overhead (telescope slew, acquisition, dither, readouts).
- We anticipate 27 min loss due to LTCS interrupts, mainly a consequence of the long integration time.

Using these assumptions, we derive that it will be possible to observe 3.14 science fields including the telluric standards and two flux standards for an average night of 10.25 hours numbers.
The total observing efficiency (open shutter on science, including standards) is 83%.

Assuming 3, 5 and 6 deployable units used (minimum, median, maximum, respectively) on the science targets, this leads to **9 to 19 observed targets (16 median) per full observing night.**

11.1.2 Observing model

The PI astronomer and her/his team would need 10 to 21 full observing nights to collect data for ~ 200 objects. Assuming a weather-loss fraction of 0.25 (KAON 463), this requires 14 to 28 allocated nights (spread over a few semester) to collect the needed sample of data.

Astronomers are requesting half to full night(s) for this science case in classical observing mode. The astronomer(s) will be performing the observations remotely (either from Waimea or elsewhere) and assessing the data quality on-the-fly. The observations require less than 1 mag of extinction in the V band (for the use of lasers). The PI and the science team are responsible for the backup observing program.

The science instrument configuration will be detailed during the Preliminary and Detailed Design phases for NGAO in parallel to the studies for the d-IFS.

KAON 548 provides details for the d-IFS: a spaxel size of 70 milli-arcsec (2 pixels of 35 mas/spaxel), a field-of-view of ~ 1.0 x 3.0 arcseconds per units (*#reqt 1.8*). Six spectrograph units deployable over a field of regard of at least 120 arcseconds in diameter.

11.1.2.1 Pre-observing tasks

During the pre-observing planning process, the astronomer will want to perform the following actions from her/his home institute:

Astronomer	Support staff	Instrument
d-IFS selection		
1. Review d-IFS performance parameters for anticipated use, e.g., sensitivity limit, wavelength, spatial and spectral resolution, science field of view, multiplexing options, etc.		1. Provides complete list of d-IFS performance parameters, including instrument configurations, relevant constrain for observing and setup, etc.
Science fields and targets pre-selection		
1. Using appropriate catalogs and other references, the astronomer pre-selects science fields and individual targets including information on magnitude, color, size (region of interest), line flux, PA, etc.		
2. For each science field, the astronomer obtains and saves coordinates for individual targets		2. Provides information on star list and coordinates format for science field and science target.
3. Determine required S/N for targets of interest. This can be point-source, extended, per spectral channel, etc.		3. Provides an exposure time calculator to aid in sensitivity and background calculations. This should include a basic S/N calculator that uses reasonable assumptions for Strehl based on typical GS brightness and distance, as well as background estimates from models. (There could be a switch to allow more detailed calculations given specific fields. The first step is a simple feasibility check.)
Science fields and targets selection		
1. The astronomer reviews main requirements affecting final targets selection for this choice of instrument setup: e.g. maximum distance to guide stars (GS), GS brightness and morphology, telescope pointing limits, etc.		1. Provides a narrative of target selection rules applied by the AO Guide Star tool.
2. For each science field, search and save coordinates for possible AO Natural Guide Stars		2. Provides an AO Guide Star tool that will search catalogs available on the internet (ADS, NASA, etc) and extract the coordinates, brightness (visible and NIR) and color information for a list of science field coordinates.
		3. For each science field information set, the GS tool will derive and save various configurations for the GS selection. • Each science field might present various possibilities for the AO GS configurations.

		• A set of selection rules will be used to quickly derive the most favorable GS configurations (e.g, based on brightness/distance).
4. Use the available tool and the observing information to derive general NGAO configuration and check for any problem.		4. Given the characteristics of the science target(s) (e.g., number of field(s) and corrected field of view – largely based on the instrument selection/setup), a tool will identify and recommend a general configuration for the NGAO system (e.g., laser asterisms geometry, PnS on AO GS, etc.)
5. Astronomers review the target + AO GS list and prioritize their target list based on science priority, anticipated image quality, and other relevant parameters. The astronomer might choose to keep at least 2 or 3 GS configurations for each science field.		5. For each science field and GS configuration, the tool will return a first-order performance metrics (based on a NGAO performance look-up table as a function of primary observing and system parameters).
6. Given the possible complexity of the star list the astronomer will use a tool to manage, view and consolidate the star list information. The list can be edited by the astronomer to add point-like source coming from other bibliography source; or to edit specific information. The astronomer will use this tool to save the starlist in various required format: LCH submission format, telescope format, astronomer format, or any specific syntax required.		6. A starlist tool allows the user to easily manage the starlist information (including coordinates for science fields, science targets, AO GS configurations, acquisition reference source and science reference source).
Pick-off alignments		
1. Review the sources in the science fields and identify: - which source(s) will serve as a reference for fine centering (if applicable) - the reference center for the laser asterism - the methodology for sky background		1. A pick-off alignment tool simulates and overlays the location for the pick-off arms over the sources in the field and the LGS.
2. Selects a geometry for the pick-off alignment for the individual IFS and saves it (with the starlist information - **TBC**). Three parameters need to be defined: field orientation (PA), coordinate for the center of the LGS asterism and anticipated dither geometry (*these values might be easier defined in instrument coordinates as the LGS needs not to move wrt to the science center*).		2. A pick-off alignment tool simulates, checks and saves the location for the pick-off arms for the science target(s), the AO GS, and the LGS. Particularly, in the case of n science targets, one needs to define the center of the LGS asterism with respect to the science priority and the IFS used for the science field.
Simulate NGAO performance on science fields		
1. The astronomer provides the science fields coordinate list, including individual science targets and NGS guide stars.		1. For each science field and GS configuration, the tool will return a performance metrics (based on a NGAO performance look-up table as a function of primary observing

		parameters and a library of PSF).
2. The astronomer provides an observing setup including observing wavelength and spectral resolution, an observing date/time (or air-mass), and selects an observing conditions scenario (e.g., x% percentile seeing conditions, wind conditions – cloud cover will certainly not be an option)		2. Includes a library of Mauna Kea atmospheric conditions for the relevant parameters used for the AO simulations. The tool allows the user to define the expected airmass range and a range of observing conditions within the library.
3. The astronomer selects the output format for the AO performance on the science targets.		3. For each observing case, the simulation tool outputs a simulated performance at the location of the science target. The AO performance includes the values for Strehl ratio, FWHM, Ensquared Energy (assuming a pixel geometry), residual TT rms, and TBD. The tool will deliver a model PSF representative of the average AO performance over 5 min with the selected observing conditions.
Simulate the instrument performance: SNR tool		
1. The astronomer provides: • The output PSF profile from the NGAO simulation tool • A spatial (and spectral?) model for the object (format TBD, but examples might include selecting from typical galaxy and stellar spectral templates as well as standard $r^{1/4}$ and exponential surface brightness profiles with specified scale lengths) • A total flux expressed in TBD photometry system (mJ, ergs.s-1, mag/ sq. arcsec)		1. The SNR tool takes as inputs: • The output PSF profile from the NGAO simulation tool • A spatial (and spectral?) model for the object (format TBD) • A total flux expressed in TBD photometry system (mJ, ergs.s-1)
		2. The SNR tool includes routines, data libraries and documentation for: • Sky emission flux model (airglow + continuum) • Transmission and background emission model for the telescope + AO + instrument • Model templates for the spatial (and spectral?) model for the object (format TBD)
3. The astronomer uses the tool to derive signal-to-noise ratio for selected integration time and observing setup.		3. The SNR tool estimates the signal-to-noise per pixel as well as integrated SNR, based on a model for the instrument for the observing setup. The instrument model will include: • A model for the detection noise, depending on detector readout options.

		• Reference sensitivity numbers for the instrument (e.g., instrument optics transmission, detector QE, % linearity vs. deep-well, zero-points) • Options for errors in sky subtraction (e.g., photon noise only, x% increased residuals due to OH airglow variations)
Observing sequences planning		
1. The astronomer enters or selects the observing parameters for each observing sequence for the science object: object name, target list integration time, filter selection, dither pattern (number and coordinates), spatial and spectral observing setup, etc. A good starting reference for planning the observing sequences for the science instrument is the OSIRIS Observations Plannng Gui (OOP Gui). Note that the OOP Gui does not include the full set of information such as location of Guide Stars		1. The tool is used for planning the observations in all possible details, including information on targets and guide star coordinates, field orientation per science target, filter sets, dithers, sky positions, etc. The planning tool uses the coordinate information to display the location of the science fields, the guide stars, and the AO field of regard, hence allowing the user to check the field geometry in either sky or instrument coordinate systems. The tool generates a finding chart for the guider field of view using e.g., DSS, etc. This can be saved/printed and used while observing at the telescope to aid in field identification.
2. The astronomer simulates various observing scenarios and save the final selected planning sequences.		2. The planning tool estimates the observing efficiency for the observing sequence (i.e., not including the AO acquisition or the calibration standards). The accompanying documentation provides information on observing overheads such as detector readout, dithering overhead, etc.
3. During observing, the observer will load up the observing sequences using the same tool, check these sequences one more time, make changes if necessary and command their execution.		3. The planning tool will be used during observations to check the observing sequences and save the file that will be used by the observing sequence execution Gui.
Calibration sequences planning		
1. The astronomer reviews the required calibration: fine centering source, telluric standard, photometric standards, darks and flats, skies, PSF. TBD: case of the standard star(s) require AO GS and LGS.		1. The documentation provides information on the required calibrations.
2. The astronomer simulate various calibration sequences and save the planning sequences. Particularly, there could a case where additional source(s) in the science field could serve as reference for fine centering, telluric or photometric standard, and/or PSF calibrations. The		2. The planning tool is used to simulate and save the instrument configuration for calibration sequences.

source could be observed simultaneously in the science field with one of the d-IFS arms.		
3. The astronomer determines the requirement for the PSF calibrations, and prepares the corresponding observing sequences.		3. Provide documentation on PSF calibration procedures and expected performance.
Laser Clearing House target submission		
1. The astronomer produces a list of all science fields requiring laser propagation including coordinate information for the science targets and the AO GS in a **TBD** format. In addition, the list includes information on brightness, color and morphology for each AO GS in **TBD** format. *At this point, we think it is not necessary to include details from 1) the observing sequences in LGS mode (yet, large offsets with LGS could require an additional pointing for LCH clearance); 2) target information for the observing sequences performed in NGS mode.*		1. The star list tool allows the user to save a star list in the coordinate and list format required for LCH.
2. The astronomer sends the list to the Observatory at least **TBD** (working) days in advance of the observations.	2. The Observatory staff uses a LCH coordination tool that collects the star list information per night (likely from formatted emails) and consolidate it (e.g., add engineering pointings or other astronomers' data). The staff uses the LCH coordination tool to send a notice message to the observer(s) that includes the target list information sent for LCH approval.	2. The star list tool allows the astronomer to submit the star list to Keck. A LCH coordination tool receives the target list from the observer. The tool has access to Keck data base for managing and using observer information for a given observing night.
3. The astronomer checks the list sent by email from Keck, and sends a formatted reply back to Keck.		3. Upon positive reviews from the astronomers, the LCH coordination tool submits the list by email to LCH.
	4. The LCH coordination tool receives the times where laser propagation is precluded from LCH and format it for the observing planning and execution tools.	

Table 23: Pre-observing tasks for example observations

11.1.2.2 Observing tasks

Astronomer	**Support staff**	**Instrument**
Target selection		
1. The astronomer selects the next science targets among the planned observations. The astronomer checks the target field status for observation planning: target field uptime, laser traffic control clearance during the anticipated observing time, etc.	1. The support staff checks the science field observability status: target field uptime, target submitted to LCH, LCH no-propagation windows, laser traffic control clearance, etc.	1. A tool provides information and status on observability using LGS for the science targets. The tool displays: telescope limits and target uptime, target LCH status, laser traffic control status on target, etc.
Field identification		

1. The astronomer prepares the necessary information to review and ID the field in the R wavelength range: R-band finding chart from the pre-observing planning tool, etc.	1. Command telescope slew and request setup for NGAO (acquisition, laser, AO, pick-off alignment, instrument) based on observing sequences information.	1. Given selection of instrument, number and coordinates of science targets and guide stars, pick-off alignment information, the tool output a configuration for NGAO sub-systems (acquisition, laser, AO, etc). This tool can run in a preview mode in the afternoon during observing checkup. Execute setup commands for NGAO (acquisition, laser, AO, pick-off alignment, instrument) based on observing sequences information.
2. Once the telescope is pointing at the science field and the field rotated as requested, the astronomer helps ID the field using the acquisition camera display, a catalog image of the same field and any additional information. Astronomers use the AO guide stars as a reference in the R-band.	2. Assesses whether the telescope pointing needs to be adjusted on a nearby reference star and find the tar star *(note that this could be fully automated by inserting a telescope pointing star for every science field)*; Based on the AO guide stars, ID the field using the acquisition camera display, a catalog image of the same field and any help from the acquisition system and the astronomer.	2. The acquisition system displays simultaneously the on-sky recorded image, a catalog image of the field at the same wavelength, orientation and scale, and the coordinates and information for the AO guide stars. The tool attempts to cross-correlate the two fields and ID the brightest objects. The ID information for the brightest GS in the field is overlaid to the recorded image to be viewed by the astronomer and support staff.
Science fields and guide stars acquisition		
1. Review the science instrument setup.	1. Monitors the progress on the science fields acquisition by checking that the AO GS is registered with the location of the probe arms (e.g., counts on LOWFS). *Note that this is an off-axis acquisition where the pointing origin is re-defined for each new science field geometry (not currently implemented with Keck AO).*	1. The acquisition software (MAGIQ) estimates the telescope offset and applies this offset. The science field acquisition is performed by registering at least one AO GS with a pixel location on the acquisition camera (pointing origin) such that the science target(s) are registered with the pointing origins corresponding to the center of the science detector(s).
2. Monitor the AO performance during acquisition and wait for go-ahead from support staff and system!	2. Monitors the progress of NGAO acquisition. There should be any manual acquisition step as it generally slows down efficiency and reliability. Gives the go-ahead to the astronomer when NGAO acquisition completes.	2. The NGAO software commands the LGS and LOWFS acquisition, closes the loops and optimizes the system performance. The software informs on "AO readiness" when NGAO acquisition is complete and performance is optimized.
Fine centering		
1. Fine centering is checked by observing one of the science target (or any identified source in the field) bright enough and visible in one sky-subtracted integration; Case 1: the AO GS are well centered for the pre-defined pick-off coordinates: the fine centering checkout observations will be performed without pre-offset. Case 2: the AO GS are all de-centered for the pre-defined pick-off coordinates: the fine centering checkout observations will be performed after a	1. Monitors the execution of the automated observing sequences for Case 1. Inform the observer and coordinate/confirm the re-centering actions for Case 2.	1. The NGAO system identifies the source(s) used for fine centering from the observer star list information.

pre-offset estimated from the average positioning error.		
2. Blind fine centering: when none of the science target (or any identified source in the field) are bright enough and visible in one sky-subtracted integration; Case 1: the AO GS are well centered for the pre-defined pick-off coordinates: science observations will be performed without pre-offset. Case 2: the AO GS are all de-centered for the pre-defined pick-off coordinates: science observations will be performed after a pre-offset estimated from the average positioning error.	2. Monitors the execution of the automated observing sequences for Case 1. Inform the observer and coordinate/confirm the re-centering actions for Case 2.	2. The NGAO system may re-position each pick-off arms to minimize the centering error.
Observations on-source science fields		
1. Load the observing sequences	1. Monitors the execution of the observing sequences.	1. NGAO system (including instrument) provide the tools to load, execute and monitor the progress for the observing sequences.
2. Monitors the execution of the observing sequences.	2. Monitors system performance variables such as LOWFS photometry and AO performance.	
	3. Monitors NGAO health and fault detector.	
Dither on the science field		
1. Monitors the execution of the observing sequences. The dither pattern is defined in the observing sequences and the pattern cannot be changed on-the-fly. The pattern can be defined in sky or instrument coordinate systems for a given sky orientation.	1. Monitors the execution of the observing sequences.	1. The NGAO system dithers the science targets around the science array with minimal overhead - by repositioning the science pick-off only, for move if the pick-off FoV permits - or by repositioning all pick-off (case dither amplitude is larger than pick-off FoV) - See KAON 558
2. Monitors the image quality as frames are being recorded and display.		TBD: requirements for the on-the-fly DRP (minimum—allow observer to select a “sky” frame and provide sky subtracted data cubes of each exposure).
Calibrations: telluric and photometry		
1. Performs the necessary calibrations required by the data reduction pipeline.	1. Provides support for the required calibrations. The requirements for the flat-field and spectral calibrations required by the data reduction pipeline will be detailed during the study and design of the d-IFS.	1. Provides documentation, characterization and support for the required calibrations.
2. Load and execute the observing sequence for the telluric and photometric calibrations.		
3. Calibrate the PSF possibly using one of these methods: 1) PSF monitoring using one IFU, and/or 2) PSF		3. The NGAO system records ancillary data and provide the tool for reconstructing the PSF.

reconstruction based on ancillary telemetry (WFC and Cn^2 data). *The first scenario is costly to science as it requires dedicating one probe arm to the observations of a point-like source but provides a simultaneous PSF calibration for one location in the field. Extrapolating the PSF measured on one location to any location in the corrected field has been demonstrated (Britton 2006).*		
	Data reduction pipeline	
1. Astronomers use Quicklook DRP to assess the quality of the data.		

Table 24: Observing tasks for example observations

11.1.2.3 Post-observing tasks

Astronomer	Support staff	Instrument
	Nightly data saving	
1. Burns a DVD or backup the nightly data (science, calibrations and quality logs): - raw and reduced IFS science data - raw and reduced IFS calibrations data - intermediary and final products for PSF calibrations and reconstruction - image quality monitoring data (e.g., TBD time averaged of rms wavefront error, LOWFS photometry, Cn^2 profile, seeing) - system status monitoring data (e..g, pick-off coordinates, telescope coordinates, system faults) - **TBD**		1. All data used for data reduction, calibrations and scientific analysis are organized hierarchically, referenced and stored in one location, accessible by the user for backup systems: A copy of the entire data set is archived at the Observatory.
	Data reduction: PSF calibration post-processing	
1. Astronomers reviews the reconstructed PSF for each individual integration frame.	1. The support staff monitors the cron jobs that produces the PSF calibration files either in pseudo-real time or after the observing night.	1. The system produces a PSF calibration file by reconstructing the time-averaged PSF for each individual observation file (using NGAO telemetry data and Cn^2 profile). **PSF reconstruction methods and intermediary and final PSF calibrations products are TBD.**
	Astronomical data reduction	
1. Astronomers use the Astronomical DRP to produce the final version of the reduced data used for data analysis. *Requirements:* ***TBD*** *(should be part of the instrument PD)*		

Table 25: Post-observing tasks for example observations.

11.1.2.4 Simulation results

11.1.2.5 Issues identified

12 References

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