NGS and LGS Acquisition Subsystems for NGAO: Initial Requirements and Conceptual Design

KECK ADAPTIVE OPTICS NOTE 567

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March 6, 2008

ABSTRACT

This note outlines the requirements and a design 'concept' for acquisition sensors to be used in conjunction with the Next Generation Adaptive Optics (NGAO) system at Keck Observatory. This work was part of the system design phase of NGAO, a standard phase of new instrument development at W. M. Keck Observatory. The note contains results from a trade study between near IR and visible detector technologies; we find that a commercial CCD is sufficient for the NGS acquisition task. A single camera design is feasible for LGS and NGS acquisition using a CCD sensor. The use of the single CCD sensor will cause relatively minor modifications to the overall NGSO optical design. High level requirements and interfaces to other NGAO subsystems are also discussed.

Table of Contents

1. Introduction

Before adaptive optics observations can begin, the various NGAO sensors and science instruments must be pointed at their respective targets. This task is referred to as acquisition. Typically, most AO wavefront sensors and science instruments have relatively small fields of view and separate relatively wide field imagers to accomplish the acquisition task. The NGAO management team [1] envisioned that such sensors would be required for acquisition of science targets, natural guide stars for low order wavefront sensing, and positioning of laser guide stars. The NGAO WBS dictionary [1] includes a design task for laser guide star (LGS) and natural guide star (NGS) acquisition sensors. The design team developed a plan [2] for accomplishing this task. The plan included:

- Requirements
- Description of interfaces to other parts of NGAO
- Design of the two acquisition systems at a conceptual level
- List high cost/risk items
- Highlight areas for further study during the preliminary design phase.

This document is the final report of that design effort for the natural guide star (NGS) sensor. The design of the laser guide star sensor is covered in a separate Keck adaptive optics note (KAON).

2. Overview of the NGS acquisition subsystem

This document develops a concept for acquiring the natural guide stars and providing a means of transferring their coordinates to the natural guide star and low-order wavefront sensors. This sensor will also be responsible for transferring science target coordinates to science instruments.

The term natural guide star (NGS) used throughout this document refers to astronomical sources with an apparent radius of a few arc seconds or less. Such objects are routinely used for wave front sensing with the current Keck AO system. In the majority of cases, the object is in fact a star. However, other astronomical sources are also used for this purpose. These include asteroids, planets, satellites, binary stars, quasars, and the core of some active galactic nuclei (AGN).

The term science target used throughout this document refers to astronomical sources acquired on the science instrument detector for the purpose of scientific research. Note that scientific targets, particularly extragalactic sources, are very likely to be too faint to be imaged at all on the NGS acquisition sensor. In these cases, relative coordinates from another object that is visible in the field of view must be known. The visible object is then used as a reference for locating the unseen faint galaxy.

The term pointing origin (PO) is used to define a pixel location on the acquisition camera that corresponds to a reference for the acquisition process throughout the observing sequence. The PO is operationally defined. It can correspond to many different locations including: the optical-axis of the NGAO system, a center of a science array, etc. For more information on Keck coordinate systems, see reference [3] by Lupton.

To avoid confusion, we use the standard photometric bands of Johnson-Cousins [4] with extensions to infrared wavelengths. These photometric bands are designated U, B, V, R, I, J, H, and K. The photometric absolute flux calibrations for U, B, V, R, and I bands are taken from Cox [5]. The flux calibrations for J, H, and K bands are taken from Wamstekeer [6]. We use the term visible detector and visible camera to mean a generic system whose wavelength response is comparable to silicon that is approximately from 0.35-1.0 microns which covers the U, B, V, R, and I photometric bands. When referring to a visible band photometric magnitude, we will use standard V letter designation for that specific band. We use the term near-IR detector to designate cameras and detectors that are sensitive from 1.0-2.5 microns.

The required tasks for the NGS acquisition system include target identification and telescope pointing correction for the following subsystems:

1. Science targets for narrow field science instruments
2. Science targets for the d-IFS spectrometer channels
3. Science targets for the interferometer tracker
4. NGS sources for low order wavefront sensor (LOWFS) channels
5. NGS sources for the point spread function (PSF) camera
6. NGS sources for the truth wavefront sensor (TWFS)
7. NGS sources for the high order wavefront sensor (HOWFS)

The NGS acquisition system will image astronomical sources on a camera and will allow the operator to position the telescope such that the object of interest will be aligned with the sensor of interest. The NGS acquisition process ends when the telescope is positioned such that the sources are aligned with the expected pixel location of the sensors. In other words, the NGS acquisition success criterion is that the guide stars are registered with the pointing origins or pixel references for the various sensor mentioned above. In a parallel phase, not covered by this document, the pickoff arms or steering mirrors will be positioned; the sensor will monitor the NGS flux, adjust its setup if necessary, and, in the case of wavefront sensors, close the AO loop.

In order to make the acquisition process more definite for the reader, we propose the following simplified procedure:

Retrieve Target Information: Read target name, coordinates, brightness of NGS, brightness of science targets, and offset to pointing origin from database or observing sequencer. The pointing origin must be stated in the observing information. A position table or image of the field is also retrieved. Ideally, the needed information is compiled during daytime hours using the observation setup tools.

Slew Telescope: Command telescope to move to new target.

Setup: During telescope slew, setup acquisition camera. Filters, readout mode, and integration time will be based on queried target information. In parallel, the AO systems and science instrument are also configured.

Record Image: Upon the completion of telescope move and any opto-mechanical setup tasks, trigger image exposure. The integration time, binning, filter, and shutter mode will depend on the brightness of the object(s) in the field.

Process Image: When detector readout is complete, perform simple image reduction including: dark subtraction, pixel-to-pixel non-uniformity correction, bad pixel repair, and cosmic ray rejection. Orient the image as necessary, including flips and rotations. Correct for image distortion as necessary to calibrate the astrometry solution.

Identify Sources: Perform algorithm to identify sources in field against known field information from the previously retrieved position table or image. Display identification results and confidence to the observer and operator. The results should be given with their confidence level. An operator can overwrite any result.

If ID Successful: Calculate telescope offset to center the telescope on the pointing origin and possible offset for all relevant science instrument and NGS wavefront sensors.

If ID Not Successful: Follow a trouble-shooting tree. Possible action might include: increasing the integration time, verifying telescope pointing by moving to nearby reference star, verifying correct position angle as this can effect image rotation, start automatic search algorithm; for example, a spiral search pattern about the assumed position.

Command Telescope Move: Once source ID is successful, then command an offset in telescope position based on the calculated distance.

Science and NGS Target Capture: Upon completion of the telescope offset, the various sensors should be set and ready to start a "NGS capture algorithm" for their respective sources. If one or more sensors fail to capture their NGS, a trouble-shooting tree for this situation will be followed which could include repeating some of the steps above.

3. Star catalogs

In this section, we review the currently available and planned all sky surveys. These surveys would be used as guide star catalogs for NGAO. Below we discuss the properties of each one that are likely to be completed when NGAO is commissioned.

3.1. USNO-B

The USNO-B catalog is an all-sky catalog that presents positions and proper motions in various optical pass bands (equivalent to B, R, and I). The catalog contains star/galaxy estimators for ~10^9 objects. Monet et al. [7] states that the catalog to be complete down to V = 21, with 0.2" astrometric accuracy, 0.3 magnitude photometric accuracy, and 85% accuracy for distinguishing stars from non-stellar objects.

An improved proper-motion catalog combining USNO-B and SDSS [8] presents data that are 90% complete for g < 19.7 (which is an updated completeness limit for the USNO-B). The astrometry for USNO-B has been improved by 20-30% down to ~3mas/year and the proper motions are placed on an absolute reference frame using the SDSS galaxies. The catalog is available via ftp. The USNO-B catalog has also been cleaned for spurious effects including optical artifacts (~2.3% of USNO-B) and the new catalog is available at astrometry.net [9].

3.2. GSC-2

The Guide Star Catalog 2 (GSC-2) is a new all-sky optical catalog based on 1" resolution scans of the photographic Sky Survey plates, at two epochs and three band passes, from the Palomar and UK Schmidt telescopes. This all-sky catalog will ultimately contain positions, proper motions, classifications, and magnitudes in multiple band passes for almost a billion objects down to approximately B magnitude of ~20.5 and an R magnitude of ~19.5. The native photometric system of the survey is based on photographic plates and the limiting magnitudes are Jpg (Blue) = 21 and Fpg (Red) = 20.

Looking ahead, the GSC-2 will form the basis of the Guide Star Catalog for JWST. As a result of its anticipated use with JWST, several studies [10, 11] have been performed on the conversion of GSC-2 magnitudes to near infrared magnitudes, specifically Johnson J band. These studies find that GSC-2 is complete to magnitudes slightly fainter than J = 17. The GSC-2 catalog has low contamination by objects not suitable for use as LOWFS guide stars. The contamination fraction to J = 19 is only 5-10%. Although GSC-2 is complete only down to J = 17, there are significant numbers of stars in the catalog useable as guide stars down to magnitudes as faint as J = 20. These stars are predominantly blue since they come from a photographic survey, but they are still suitable for use as guide stars. The "missing" stars (i.e., IR-bright stars not detected below the completeness limit of GSC-2) amount to an approximate 25% increase over the number of cataloged stars. More information about the GSC-1 and GSC-2 can be found at http://www-gsss.stsci.edu/Catalogs/Catalogs.htm.

3.3. 2MASS

The 2 Micron All Sky Survey (2MASS) is a J, H, and K short (K_s) infrared survey of the full sky. The catalog consists of seeing limited observations with an angular resolution of about 2 arc seconds. The completed catalog will contain over 470 million sources. Its limiting magnitude is approximately J = 15.2. The contamination rate is measured to be ~11% [10], presumably due to unresolved compact galaxies. The 2MASS catalog will be merged into the GSC-2 to better support JWST observations [11]. Further information about this survey can be found at http://www.ipac.caltech.edu/2mass/.

3.4. SDSS

The Sloan Digitized Sky Survey (SDSS) is a 5 color survey in bands that span 300 nm to 1.1 micron in wavelength. These optical bands are designated u, g, r, i, and z with 95% completeness limits for point sources of 22.0, 22.2, 22.2, 21.3 and 20.5, respectively in the SDSS photometric system. The survey covers most of the Northern Galactic hemisphere above galactic latitude of b=35º with less coverage in the southern regions of the sky. Hutchings [12] determined a conversion between the SDSS magnitude system and the Johnson J magnitude along with star density measurements that are consistent with the NGAO error budget (i.e. Spagna star model). The SDSS survey is complete to about J = 19.1. Comparing SDSS data to HST observations [13], the rate at which galaxies are misclassified as stars is insignificant in this catalog. The star counts predicted by Galactic models, along with the results of a deep CFHT study by Hutchings et al. [14], support the Spagna model which is the basis for NGAO sky coverage predictions. Based on these properties, the SDSS would be sufficient for NGAO natural guide star selection. The limiting magnitude for LOWFS stars is estimated to be J = 19 by Dekany [15, 16]. In general, the SDSS survey gives superior photometric information than surveys based on photographic plates such as USNO and GSC-2. Further information on this survey can be found at http://www.sdss.org.

3.5. DENIS

The Deep Near Infrared Survey (DENIS) is a three-color survey taken over (SDSS-i; J and Ks,) with limiting magnitudes 18.5, 16.5, and 14.0 respectively. The catalog's limiting magnitude of J ~ 16.5 and coverage of only the Southern Celestial Hemisphere limits the usefulness for NGAO at Keck. Further information can be found at http://cdsweb.u-strasbg.fr/denis.html.

3.6. WISE

The Wide-field Infrared Survey Explorer (WISE) is an all-sky 4-channel mid-infrared survey from 3.5µm to 25µm with about 2" resolution at the shortest wavelength. WISE will produce a catalog that includes M dwarfs with equivalent J magnitude of about 17. WISE has been confirmed by NASA headquarters and is under construction. The launch is scheduled for late 2009. The mission lifetime is planned to be one year. The all-sky catalog would presumably be available sometime after the end of operations around 2012. Any delays in launch would likely delay publication of the catalog until after NGAO is commissioned. Further information can be found at http://wise.ssl.berkeley.edu/.

3.7. VISTA

The Visible and Infrared Telescope for Astronomy (VISTA) is planned to be installed at ESO in the southern hemisphere. Observations will be made by a 4m telescope with a 1 square degree FOV and 0.34" pixels in J, H, and Ks. Its primary scientific objective is to conduct "targeted" surveys beginning in about 2006 and completing about 2012. It is not intended to be a southern all-sky survey. The location, like DENIS in the Southern Hemisphere, limits its usefulness for Keck. Further information can be found at http://www.vista.ac.uk.

3.8. UKDISS

This survey will use the UKIRT telescope on Mauna Kea to survey the northern sky in selected areas of interest. The survey with be made in 5 photometric bands that cover from 1.0 to 2.5 microns wavelength, in its own Z, Y, J, H, and K filters. The Large Area Survey (LAS) will reach near infrared magnitudes in the J band of about 20. The UKDISS survey is planned to finish in 2012. UKDISS will likely be an important supplement to the SDSS for NGAO when the survey finishes. Further information about this survey can be found at http://www.ukidss.org/surveys/surveys.html.

3.9. Future surveys and conclusions

Once NGAO is commissioned, many large all-sky surveys will be operational or just coming online including Pan-STARRS and the LSST. The Pan-STARRS may face delays over permitting at its preferred locations on Mauna Kea or Haleakala. The LSST will be located in the Southern Hemisphere so it is only able to observe the part of the sky accessible at Keck. Therefore, it appears that at NGAO first light the GSC-2 and the SDSS will be used to provide general guide star information for observers with other surveys providing supplementary information where available.

Although it is intuitively appealing to suggest that a NIR acquisition camera would first record an image of the field around the astronomical target in order to select science targets and LOWFS guide stars, we note a few problems with this approach. The image would have to be analyzed for possible natural guide star combinations that provide the best performance for the LOWFS. The optimization of the LOWFS natural guide stars is a complex trade between star brightness and anisoplanatism. The overhead for this process appears to make it unsuitable as a standard operational model. A more reasonable model is that during daytime setup, the observer would query one or more standard star catalogs mentioned above and use that information to determine the optimal configuration for the LOWFS natural guide stars for all science fields for the upcoming night of observing. This process could use the GSC-2 catalog supplemented with the SDSS catalog which would provide enough LOWFS targets to meet the NGAO performance requirements. In this case, the acquisition detector can be either a NIR or visible type as the task of field identification in the infrared has been transferred from the detector to the catalog.

4. NGS acquisition scenarios from science cases

Our object here is not to look at the full acquisition probability as it has been developed by the JSWT [10,11] but to understand the acquisition requirements and the risks, then propose a design.

The NGAO planning tools will query the astronomical catalogs and provide the information around the science field that will allow the observer to derive the position, NIR brightness and color for the NGS, and plan for the observations. Then, during the NGS acquisition process, the on-the-fly information collected by the acquisition camera needs to overlap, complement, and concur with the information collected from the catalogs and allows the registration of the field. In most cases, the astronomer will have planned the observations and will have selected a set of natural guide stars of J< 19 to be used with the NGAO sensors. In addition, the required information from the planning tool will include the position, brightness, and color of the sources on the science field at the acquisition camera observing wavelength. The difficulties in acquisition will reside in situations where:

1. The telescope pointing information is erroneous by about a field of view of the acquisition camera.
2. Mismatch between the on-the-fly information and information from the planning tools:
    - Erroneous data from the catalogs or literature, including contamination by galaxies and binary stars.
    - Missing data from the catalogs (e.g., low completeness fraction of M stars of J~19 in GSC-2).
    - Poor camera sensitivity for the particular source; for example, a visible camera observing in an area with very high extinction such as a molecular "dark cloud".
3. The numbers of identifiable objects in an image is small due to
    - The physical nature of the field, for example the galactic north pole.

- Periods of poor atmospheric transparency such as cirrus or thicker clouds.
- Very high contrast ratios for the sources in the science field (e.g. locating and acquiring a faint satellite in the close vicinity of a giant planet).

Our first point depends on the telescope pointing and is discussed in section 6.1. The third point depends on the observing conditions and the dynamic range in the images from the acquisition camera. The situation can be improved by using specific filters. The second point requires particular attention: The study for JWST by Kriss & Stys [10] estimate a contamination fraction of 5-10% in the GSC-2 catalog for J=19, compared to SDSS. The contamination is mostly due to galaxies with some contribution from stars and other effects. In addition, the authors report a 1-2% contamination fraction from binary stars unseen in both the SDSS and GSC-2 catalog, but observed by HST [10]. More recently, Lava [17] reviewed published stellar multiplicity study surveys and showed that the multiplicity is a function of spectral type and varies from 57% for the G stars to ~15% for brown dwarfs, with a secure estimate of 26% for the M stars. The author concludes that most stars are single. The risk of acquiring a binary star that can be resolved by the NGAO sensors exists but remains under < 5%.

The use of a diaphragm for well-separated NGS binaries at the resolution of the sensor can mitigate the risk. Another option is for the LOWFS to be able to use resolved objects as a reference source. Careful pre-observing planning using multi-wavelength archive data can mitigate the risk for galaxy contamination. Some galaxies present steep intensity profiles and can serve as NGS references as long as the LOWFS can use these partially resolved objects.

Existing sky surveys in the optical are more complete for star census than existing NIR surveys. Yet, the estimation of the NIR flux and color based on incomplete optical data set may lead to some errors. If the NGAO system (planning tools + acquisition information) fails to provide an accurate estimate for the NIR flux for the NGS before the stars are acquired on the LOWFS, this may lead to significant overhead (full re-acquisition?) in order to optimize the NGS asterisms with respect to the sensors (TT, TTFA, TWFS).

We propose to review succinctly a few acquisition paradigms and their possible associated challenges from the science cases developed for NGAO [18]. The results are presented in Table 1 and Table 2. For each table, the first row shows the science cases. In the second row, we list the assumptions for this science cases. In the next row, we anticipate the information that will be available for the NGS stars. Row 4 is an attempt to look qualitatively into the risks. Finally, row 5 is a first-order assessment of the merits of optical and NIR detectors.

Table 1: Acquisition consideration for NGAO science cases X1-X3, and G2-G3

Science cases	**High-z galaxies on d-IFS (X2)**	**Gravitational lenses by galaxies (X4)**	**Imaging QSO in the NIR (X1)**	**Nearby AGNs and Galactic Science (X3 - G2 – G3)**
Assumptions	- Field is known. - Field has been surveyed at different wavelengths down to ~100 mas spatial resolution.	- Field has been surveyed by Hubble (see SLACS). - Seeing limited survey images are available at optical wavelength and possibly near-IR.	- Field sometimes known, sometimes unknown. - Seeing-limited sky survey (visible and near-IR) provides field ID info.	- Field has been observed many times before and is well known. - Field has been surveyed at different wavelengths down to ~100 mas spatial resolution.
Available NGS TT information	-Vis and NIR mag. are well documented.	Vis mag < 20 to 22 (USNO, GSC-II, SDSS) NIR mag < 17 (2MASS, DENIS)	- Vis mag < 20 to 22 (USNO, GSC-II, SDSS) - NIR mag < 17 (2MASS, DENIS)	-Vis and NIR mag. are well documented.
Most likely NGS risk	0.1" or less binary Variable star Faint M stars	Mostly Galaxy < 2" binary Variable star	Galaxy Binary Variable star	0.1" or less binary Variable star
Optical versus NIR acquisition	Either to ID field NIR better for NGS	Either to ID field NIR to select NGS	Either to ID field NIR to select NGS	Either to ID field NIR to select NGS

Table 2: Acquisition consideration for NGAO science cases X5, G1, S1-S3

Science case	**Planets around low-mass stars (also astrometry in sparse field) (G1 – X5)**	**Asteroid/planets at predicted UT (S1 – S2 – S3)**	**Asteroid/planets at any given UT (S1 – S2 – S3)**	**GRB on d-IFS or narrow-field instrument (~ X5)**
Assumptions	- Field is sometime known, sometime unknown. - Seeing-limited sky survey (vis and NIR) provide field ID info.	- Field is unknown. - Seeing-limited sky survey (vis and NIR) provide field ID information. - Observation UT selected to optimize NGS selection.	- Field is unknown. - Seeing-limited sky survey (vis and NIR) provide field ID info. - May require on-the-fly NGS selection.	- Field is unknown. - Seeing limited detection images are available at optical wavelength and possibly at near-IR.
Available NGS TT information	- V < 20 – 22 (USNO, GSC-II, SDSS) - NIR mag < 17 (2MASS, DENIS)	V< 20 - 22(USNO, GSC-II, SDSS) NIR mag < 17 (2MASS, DENIS)	- V < 20 - 22 (USNO, GSC-II, SDSS) -NIR mag < 17 (2MASS, DENIS)	-V < 20 - 22 (USNO, GSC-II, SDSS) -NIR mag < 17 (2MASS, DENIS)
Most likely NGS risk	Science target proper motion (see below) Galaxy Binary Variable	< 2" binary Variable Galaxy	< 2" binary Variable star Galaxy	< 2" binary Variable Galaxy
Optical versus NIR acquisition	Either to ID field NIR to select NGS Note that the science target could have uncertain proper motion and not be detected in an optical camera. Use of NIR camera would help here.	Either to ID field NIR to optimize NGS	Either to ID field NIR to select NGS	Either to ID field Note that the science target could have uncertain position and not be detected in a optical or NIR camera. NIR to select NGS.

5. NGS acquisition camera requirements

Using the science acquisition scenarios from section 4 and the baseline acquisition process outlined in section 2, the acquisition design team identified the desired attributes for the NGS acquisition system as:

- Rapid and accurate field identification
- Efficient pointing updates
- High probability of detection for astronomical targets and natural guide stars used for wavefront sensing

Based on the analysis of the above, detailed requirements were developed and are listed in Table 3. The complete requirements are listed in Appendix A. The requirements will continue to evolve during subsequent phases of the NGAO project. Please consult the requirements database for the most up to date requirements. We next discuss each item from Table 3 in the following sections.

5.1. Field of view

One would like to use the largest field of view possible for identification of a particular astronomical field as this provides the highest probability of finding suitable natural guide stars and relaxes the tolerance on absolute telescope pointing. The NGS field of view should be at least as large as the d-IFS and LOWFS technical fields. Rich Dekany performed an analysis of the required field of regard for the LOWFS based on consideration of sky coverage in reference [15] and found it to be 150 arc seconds. Science requirements [18] place the d-IFS field of regard at 120 arc seconds or larger. We adopt 150 arc seconds as the minimum required field of view for the acquisition camera.

Table 3: Specifications for acquisition camera conceptual design

Title	Specifications
Field of view	A field of view ≥ 150 arc seconds
IR field identification	a) Image sources in the near-IR (1.0-2.0 micron) b) Image sources in the visible (0.5-1.0 micron) In both cases, use supplementary information about target locations from catalogs and surveys
Point source sensitivity	V=22 or J=19, exposure ≤ 10 s, SNR ≥ 10
Position accuracy	0.050 arc seconds rms, random errors in determining source positions in an acquisition camera image
Minimal time overheads	Total acquisition process time typically < 50 s, worst case < 120 s Includes time for telescope moves, camera exposure, and analysis.
Photometric imagery	Photometric error of 0.2 magnitudes, in standard astronomical bands such as Johnson, UKIDDS, or SDSS
Registration accuracy	0.020 arc seconds rms, random error in determining positions of acquisition camera with respect to telescope optical axis
Diagnostics and troubleshooting tools	Report metrics for automatic acquisition and to aide observer decision-making, including manual override by astronomer or observing assistant
Data products	Store acquisition images as FITS files in the NGAO data server and record appropriate diagnostics in the NGAO data server
Interface to observer planning tools	Acquisition software will receive target information from the NGAO observer planning tools
Guiding mode	Used for testing when other wavefront sensors not available

5.2. IR field identification

As detailed in section 4 the use of a NIR sensor for the LOWFS places extreme requirements on the ability to acquire faint IR natural guide stars. One solution is to use a NIR sensitive camera for the acquisition sensor. One can take images to determine the pointing information directly at the same wavelength as the LOWFS sensor. As discussed in conclusion of section 3, while setup of the LOWFS directly from NIR acquisition images is appealing, the overheads in this process make it objectionable for normal operations. A more likely scenario is to determine all LOWFS stars from catalog data before the start of the observing night. As long as the catalogs have high photometric and astrometric accuracy and they are complete to a sufficiently faint magnitude, then the acquisition step can be done with either a visible or NIR detector.

5.3. Point source sensitivity

The acquisition image for a visible detector must reach V = 22 and the corresponding magnitude for a NIR detector is J = 19. These magnitudes correspond to an M0 spectral class star which is typical of field stars at the Galactic poles. These performance levels are consistent with the NGAO sky coverage error budget [15,16] and the LOWFS design. The sensor must be able to reach these magnitudes in a reasonable exposure time of 10 seconds or less and with a signal to noise ratio of at least 10. These secondary specifications are set by the need to minimize the time needed to complete acquisition and to accurately position NGS targets. These requirements are discussed in the next two sections.

5.4. Position accuracy

We adopt a random error for positioning accuracy of 0.05 arc seconds for acquisition. The specification is better than the acquisition accuracy given in the preliminary science requirements for NGAO [18] for the case of imagers and integral field spectrographs where the acquisition accuracy is stated as 10% of the image or IFU field of view which would be 0.1 arc seconds for a 1 arc second IFU. In the case of a slit spectrograph, the acquisition accuracy is one quarter the diffraction limit or $0.25\lambda/D$. For visible instruments (short wavelength cutoff of 0.7 μm), this requirement could be as small as 3 milli arc seconds. For a NIR slit spectrograph, the accuracy is between 4 and 11 milli arc seconds. In order to achieve this level of position accuracy, the AO loops will need to be closed and small offsets put into the AO tracking loop to position the target along the slit. This is no longer a task for the acquisition system. The acquisition accuracy requirement is set at 0.05 arc seconds. Assuming a seeing limited image size for the acquisition image of 0.5 arc seconds FWHM, the formalism developed by King [19], predicts that a SNR of 10 or better results in centroid errors of 0.030 arc seconds or less. The SNR requirements of section 5.3 and the positioning accuracy are seen to be self-consistent.

5.5. Minimize time overhead

The NGS acquisition process is a serial process: the telescope pointing must be accurate and the field must be identified before the NGS is acquired on the sensor. Therefore, the NGS acquisition system should attempt to be very efficient and minimize time overhead.

The time allocation for the average telescope slew from one science field to the next is ~120 sec; this is assuming an average slew of 20-40 deg in elevation (0.5 sec/deg) and 3-5 hours in Az (1 deg/sec). Hence, the average slew time is 90 - 160 sec. While the telescope slews, the NGAO system will get configured for the target using the information from the Observing Sequencer software. This is currently the paradigm with the Keck II LGS AO system.

In Table 4, we investigate the time budget for three different case scenarios. In all cases, we assume the NGS acquisition system is configured during the telescope slews and that some of the acquisition steps are automated (this is not currently the case with the current system). In the first case, we assume the NGS are very faint (V~ 20, J~17) and will require adjusting the telescope pointing first, then performing manual acquisition even though the system has the capability to do them automatically. In the second, an average case scenario, the NGS are bright enough or the field is close enough from the previous pointing update that there is no need to go to a pointing star. Due to the brightness (and/or the number) of NGS, the field ID is automated. The third case is a best-case scenario where the NGS are bright or numerous enough so the acquisition steps can be queued and automated.

Table 4: NGS acquisition overheads

Time Allocation / Action	Worst Case Scenario	Average Case Scenario	Best Case Scenario
Setting up for pointing check on a 8 –12 magnitude pointing star	During telescope slew	n/a	n/a
Integration	2 < t < 10 seconds	n/a	n/a
Read image, ID field, and adjust pointing	2 < t < 5 seconds (automated)	n/a	n/a
Slew to science field	~ 15 seconds	n/a	n/a
Setting up for acquisition	… Mag. ~ 20 NGS During telescope slew	.. Mag. < 17 NGS During telescope slew	.. Mag. < 17 NGS During telescope slew
Integration	5 < t < 15 seconds	2 < t < 10 seconds	2 < t < 10 seconds
Read, ID field, and command offset to PO (if able)	5 < t < 30 seconds (manual mode)	2 < t < 5 seconds (automated)	2 < t < 5 seconds (automated)
Command to center on PO	5 seconds	5 seconds	5 seconds
Integration for fine centering	5 < t < 15 seconds	5 < t < 20 seconds	not necessary, centering good enough
Read, ID field, and command fine offset to PO	5 < t < 20 seconds (manual mode)	5 < t < 10 seconds (automated)	n/a
TOTAL ESTIMATED TIME (rounded up)	50 < t < 120 seconds	30 < t < 50 seconds	10 < t < 20 seconds

Note that the current pointing error of the telescope is large enough that it requires acquiring a pointing star and adjusting pointing whenever the slew is greater than about 60 degrees. So case 2 and 3 may be a little bit over-optimistic by 20 to 30 seconds (assuming the acquisition automation is in place).

We propose to use the following requirements for the design phase of the NGS acquisition system which are dependent on the brightness of the NGS and acknowledge the difficulty of acquiring fainter stars:

- The telescope pointing adjustment steps should account for less then 30 seconds overhead in the NGS acquisition phase including extra-slewing.
- The NGS acquisition should take less than 90 seconds for NGS V ~ 18-20; less than 50 seconds for NGS V < 17 with the goal of achieving less than 20 seconds for the easiest scenarios.

Note that the table above does not present any scenario and associated overheads for the case where the NGS is not suitable for NGS wavefront sensing (binary, galaxy, etc).

5.6. Photometric imagery

The NGS acquisition system should use photometric filters. These filters are yet to be defined and depend on the wavelength range for the acquisition camera. Under transparent conditions, the NGS acquisition system should provide a rms photometric accuracy of less than 0.2 magnitudes. This photometric requirement is based on current performance with the K2 ACAM system and will allow the cross identification of the sources in the field against the available literature during routine operations.

5.7. Registration accuracy

The NGS acquisition camera will be used as the reference to register the K-mirror optical axis, the LOWFS, d-IFS, and truth sensors pickoffs, as well as the narrow field science arrays. This information is required to calculate the pointing origins and perform the fine acquisition steps at the telescope. The registration is performed during the day, by imaging an internal AO simulator point source. The registration accuracy between the sensors and the NGS acquisition camera must be documented to less than 0.02 arc sec over the entire field-of-view. A registration error of this amount makes minimal contribution to the overall positioning error from the position accuracy requirement of section 5.4.

5.8. Diagnostics and troubleshooting tools

There will be cases where it will be difficult to automatically ID the science target in the image. One example is high proper motion objects. Another situation is when the NGS is resolved and too elongated to serve as guide stars for the wavefront sensors. For these cases and others not detailed here, we will want to use the NGS acquisition system in a manual mode: the operator will ID the field visually and may use optional functions available from the NGS acquisition user interface for troubleshooting the situation. Many of these functions have already been implemented in MAGIQ, see references 20 and 21. Below, we propose a preliminary list of options:

- Measure and output peak centroid, FWHM, eccentricity, and calibrated flux for any object selected in the field.
- Allow the operator to point at pixel x, y in the image, then read back RA, DEC from the image, and save these coordinates.
- Display scale and orientation on the recorded image.
- Make on-the-flight request for data to digital sky survey at an observer specified wavelength. This might require local installation of the data from the most recent surveys, e.g. GSC-II for telescope pointing.
- Allow the operator to measure distance and orientation between two points in the image.
- Output these quantities in a format so that they could be read back by the Observing Sequencer.
- Allow the operator to use simple mathematics on two images (+, -, *, /) or one image and a constant, then save the result.
- Interactive telescope offset based on a two-position click or entries from the image data.
- Overlay pointing origin location onto the recorded image.
- Overlay reticles at the NGS sensor locations onto the recorded image, providing a table of coordinates for the sensors.
- Allow the operator to overlay an image (or a table of positions) from the literature.
- Allow the operator to adjust the intensity display scales and parameters, as well as zoom in and out on an image area.
- Allow the operator to center the display on a part of the image.
- Allow automating some of these functions and generating scripts to be saved and executed later.

This list is a sample of possible capabilities. Details will be defined in later phases of the acquisition system, observer tools, and non-real time software development.

5.9. Data products

All acquisition images should be stored on the NGAO data server. Images should be in FITS file format and have standard FITS header information. The exact content of the header will be defined in subsequent phases of the project. The data product from the acquisition system and the information from available catalogs or literature should be recorded in the same photometry system and with comparable spatial resolution.

5.10. Interface to observer planning tools

The acquisition system will receive target information from the NGAO observer planning tools. It is expected that the astronomer will use the NGAO observer planning tools to collect and assemble the necessary information. The target information would include: the target name, coordinates, brightness of NGS, brightness of science targets, and offset to pointing origin. An image, sky chart, or position table is also included with the target information. This date could be from available on-line survey data or previous observations from Keck or another telescope.

5.11. Guiding mode

The NGS acquisition system must offer the capability to be used as a guider for the Keck telescope. The use of guiding with the NGS acquisition camera is anticipated mostly during the integration and testing phase of the instrument.

6. Interfaces to Keck Observatory and NGAO subsystems

In this section, we consider the systems at the Keck Observatory and the subsystems of NGAO that will interface to the NGS acquisition system. These systems place constraints on the design of the NGS acquisition system. In order for the design of the acquisition system to be successful certain performance levels will be required from these systems.

6.1. Keck Telescope

In order to minimize overhead on a new object, the NGAO acquisition system requires the telescope to be able to point so that the NGS objects appear in the acquisition sensor field of view.

> The telescope shall provide a pointing accuracy of 15 arc seconds rms and 30 arc seconds peak to valley after large telescope slews of 40 degrees in elevation and 5 hours in azimuth.

This requirement is derived from the NGS acquisition camera field of view, 150 arc seconds, as compared to the typical imager camera field of view, 40 arc seconds, and the field of regard of the NGS wavefront sensors, 150 arc seconds. In addition, the NGAO acquisition system requires the telescope to be able to center the objects in one-pointing once the field ID is complete.

> Therefore, the telescope should be able to point with less than 0.5 arc second rms error (and 1 arc second peak to valley error) for any move of less than 30 arc seconds (which corresponds to the peak to valley value for telescope pointing).

KSD 226 [22] presents a report on the Keck telescope pointing error. It is understood from the report that the MAGIQ project will not affect the pointing error in any way. The telescope pointing performance is monitored by the keywords CA and CE, collimation azimuth and elevation respectively. CA and CE represent the pointing adjustments to correct the azimuth and elevation of the telescope locally. A local correction means that it is only valid within a small area of the sky. In order to estimate the Keck II pointing error, we used the query tool [23] to request the CA and CE pointing model offset data as measured and applied on the sky, for all year-2007 nights, including all instruments. The sample data contains 2021 points. The results in Table 5 represent typical corrections applied to the pointing model. These values need to be taken with caution: there is first a bias towards worst performance as the CA and CE are only adjusted where the model shows errors that impact the science performance. There is a second bias due to the fact that we do not normalize by the location and the number of observed targets. It is known that the telescope shows higher CA correction with higher elevation. The standard deviation may be a more objective quantity, as it shows the rms pointing error, which can be interpreted as the average error once the model has been corrected. Finally, the maximum error is representative of the peak to valley error.

Table 5: Typical Keck telescope pointing errors

Parameter	Average (arc seconds)	Standard deviation (arc seconds)	Maximum (arc seconds)
CA	25.7	17.6	120
CE	34.1	14.2	190

In the optimistic case, where one takes the standard deviation as representative of the telescope pointing error, the errors in azimuth and elevation when combined in quadrature are 22.6 arc seconds. This is greater than the requirements for rms error given above. The estimated peak to valley error is also larger than the requirements. Shui Kwok [24] has reported that the second requirement of 0.5 arc seconds rms error for an offset of 1 arc minute is currently not met as well.

One could imagine that the large telescope pointing performance can be compensated by a larger field of view than the 150 arc seconds stated in section 4. More likely is the need to correct CA and CE on a star with known coordinates before attempting acquisition with NGAO. This could add up to 20 seconds additional overhead to the acquisition and was considered in the worst case scenario in section **Error! Reference source not found.**. More troubling is the large error when making relatively small moves of order 1 arc minute. We conclude that the current telescope pointing performance does not meet the NGAO requirements and that further work is required to investigate this issue.

6.2. Astronomical catalogs

The use of accurate and complete astronomical catalogs is essential for NGAO acquisition, see sections 3 and 5.2. Astronomical catalogs and image archives can be available either remotely at a data base center and queried over the internet or stored locally on disk. Currently, the Keck telescopes have the SAO, the HIP, and the GSC-1 catalogs, either in part or full. The MAGIQ user interface allows the user to send requests to other catalogs such as 2-MASS, GSC-2, and USNO 1.0B. These requests are handled through a generic interface to the catalogs and the requested data can be cached locally at Keck for a period of time typical of an observing run. These features are documented in the MAGIC design [21, 20].

In addition, one can imagine an automated tool that will make requests to all catalogs and cache the data, based on the target list for the night, reducing the need for an on-site catalog. The NGAO target list must be finalized in the afternoon the day of observing due to the need for approval from the laser clearinghouse. Additional on-line requests for last-minute NGS targets could still be addressed during the night.

The required list of astronomical catalogs for NGAO operations and observations was discussed briefly in sections 3 and section 5.2. The conclusions of these sections will be refined during the preliminary and detailed design phases of the project. Our current conclusions may change depending on the progress of several currently-planned sky surveys.

6.3. NGAO optical constraints

The working NGAO design has the AO system located at the f/15 Nasmyth focus and is composed of two optical relays that are cascaded one after the other. The acquisition design team in consultation with Don Gavel and Reni Kupke developed four possible locations for the NGS acquisition sensor. These were

1. In front of AO system, at the telescope Nasmyth focus
2. Behind first stage of AO relay and before the input to the second relay
3. After the “post relay 1 dichroic” and in front of the d-IFS/LOWFS pickoff
4. Behind the second relay

Location 4 was ruled out because the full field of view (150 arc seconds diameter) of the first relay could not be passed through the second narrow field relay. The beam was found to vignette on the tweeter DM (MEMS) in the second relay.

Increasing the opening angle on the first off-axis parabola in the second relay was found to produce unacceptably high aberrations. Location 1 was judged to be unfavorable because of the space around the bearing and the large number of non-common path optics between the acquisition sensor and the other sensors that are part of NGAO which would result in the need to calibrate the acquisition camera registration more frequently. Location 3 was favored over location 2 because of the smaller non-common path between the d-IFS/ LOWFS pickoffs and the output of the 1st stage relay. As currently understood, the d-IFS and LOWFS pickoff will have a very small FOV of order 1-3 arc seconds so the acquisition will be the most challenging for IR tip tilt stars and faint d-IFS targets.

In the current NGAO optical design, the NGS acquisition camera is located at location 3. The optical design will pass a 150 arc second diameter field of view. A separate selection mirror directs light from the d-IFS/LOWFS beam into the acquisition camera. See the full detail in design notes [25] from the optical design team. Proposed coatings for the "post relay 1 dichroic" and the NGS acquisition fold mirror are given in Table 8 of KAON 549 [25]. The choices for the "post relay 1 dichroic" beam splitters are such that with proper selection any wavelength between 0.35 μm - 2.5 μm, excluding the pass-band around the 0.589 mm, can be sent to the NGS acquisition sensor. Complete details are included in reference 25.

Table 6: AO system optical parameters for NGS acquisition camera

Parameter	Min.	Typ.	Max.	Units	Notes
Field of view		150		"	1
Wavelength	0.45	--	2.5	μm	2
Transmission		75		%	3
Plate scale		1.380		"/mm	
Pupil location		∞			4

Notes:

1. Diameter of circular field
2. Excluding small band around laser wavelength, 589 nm
3. Based on values assumed for NGS acquisition detector trade study, see section 7.1
4. Output of telescope and first AO relay assumed to be perfectly telecentric

6.4. Registration of NGS acquisition to science sensors and NGS wavefront sensors

In order to transfer pointing information from the acquisition sensor to the science instruments and the NGS wavefront sensors, each of these sensors must be registered to a common coordinate system in the same way the acquisition sensor was registered in section 5.7. Registration is performed during the day, by imaging an internal AO source that simulates natural stars. This process is straightforward for imaging science sensors and Shack-Hartmann type wavefront sensors. Just measure the location of the AO internal source in a recorded image. Spectroscopic sensors would be calibrated by walking the AO simulator point source across the slit or integral field slicer. A fit of the intensity versus point source position will be used to determine the spectrograph registration which can be rechecked as needed.

6.5. Level of AO correction

With both the higher order LGS and lower order NGS loops open, the seeing limited image FWHM at Mauna Kea varies between 0.2 and 2 arc seconds with 0.5 arc seconds being a typical value at a wavelength of 0.5 microns, while in the near infrared (K band) the corresponding value would be 0.42 arc seconds. In current AO systems, acquisition of science and natural guide stars (NGS) targets is done with the adaptive optics control loop open. Typical natural guide stars for the LOWFS will be as faint as J = 19.5 which corresponds to V = 22 for a spectral class M star typical of stars near the galactic pole. In order to acquire these faint tip tilt stars, the sensitivity of the acquisition camera can be increased significantly if the image is partially corrected and sampled to take advantage of the increased resolution. This advantage is most significant if the acquisition camera is sensitive in the near IR due to improved AO correction and higher backgrounds at these wavelengths. Alternatively, these faint magnitudes can be reached with an increase in exposure time. In addition, an AO corrected image can be used to identify objects that would be problematic for the low order wavefront sensor (LOWFS) to use as a guide star because of their extended nature. Such objects include random field galaxies and double stars with separations between 0.2 and 0.030 arc seconds. Faint galaxies outnumber stars near the galactic pole. The exact number of faint tight double stars is unknown at this time, yet the fraction of double stars unseen in both SDSS and GSC-II but resolved by HST is 1-2% [11].

The design team considered the possibility of projecting the LGS constellation and then closing only the higher order AO loops before starting NGS acquisition. Unfortunately, having only the higher order AO closed does not provide diffraction limited performance across the entire acquisition field of view. The AO system design and our desired location for the acquisition camera, behind only a single deformable mirror, results in a modest AO correction with only the LGS loops closed.

Using the NGAO error budget, Rich Dekany [26] has estimated that using only the DM in the first relay for correction results in peak short exposure J Strehl as high as 0.30 (220 nm rms) with a J band Strehl of 0.1 being more typical. The short exposure J FWHM might be as good as the diffraction limit, 0.025 arc seconds. But a more typical value across the field of view is likely about 0.1-0.2 arc seconds when the effects of anisoplanatism and blur from the lack of tip tilt correction are considered. An alternative would be to apply a "ground layer" correction to the main deformable mirror. The correction in this case would be poorer but more uniform across the field of view. Simulations of ground layer AO systems [27] predict about 2 times improvement over seeing limited performance. The ground layer FWHM in the NIR would be about 0.2 arc seconds under typical conditions. At this time, the gain from closing only the LGS loop for acquisition appears modest. The design team also considered that the tip tilt loop might be closed on the brightest star only and then subsequent acquisitions of the other NGS stars and the science stars could be made. This approach, while possible, appeared to require a large increase in overheads and complexity.

As a side note, a new and interesting science capability can be opened up for NGAO if a near-IR acquisition camera can observe while the LOWFS loop is closed. In this mode, NGAO would apply a "ground layer" correction to the main deformable mirror and the acquisition camera could observe over the 150 arc second field of view of the first AO optical relay with images between 0.1-0.2 arc seconds FWHM. The MEMS mirrors provide MOAO correction to each d-IFS "postage stamp" with higher Strehl. Combining IR imaging with the d-IFS spectroscopy might be an attractive science mode. These options would require the ability to send some fraction of the light to both the LOWFS and d-IFS (80%) and the acquisition cameras (20%) simultaneously. This could be achieved by adding additional dichroics to the acquisition beamsplitter mount.

6.6. NGAO IR LOWFS

The Low Order Wavefront Sensor (LOWFS) is at a similar state in the design process [28] as the acquisition cameras. The design is not frozen and may undergo changes in subsequent phases of the NGAO project. The current LOWFS sensor has three pickoff mirrors, each one on an arm that can be positioned about the AO field of view. The field of view of each arm is listed in Table 4 of reference [28] as 5 arc seconds with a note that this value is subject to change. A similar mechanism from the same report (Figure 5 reference 28) lists the field of view of the pickoff as 2-5 arc seconds. We assume that the LOWFS has a field of regard of at least of 2 arc seconds. Other LOWFS parameters relevant to acquisition are given below in Table 7. The current design of the LOWFS features a "gated" tracker that can readout many pixels and then shrink the region of interest as the object is centered down to a single 2 by 2 pixel quad cell. The feature is implemented to allow tracking on extended objects.

Table 7: Low Order Wavefront Sensor parameters relevant to acquisition

Parameter	Min.	Typ.	Max.	Units	Notes
Pick off field of view	0.06	2	5	"	
Tracker sensor field of view	0.06	2	5	"	
Wavelength	1.0	–	2.5	μm	
Plate scale	–	0.030	–	"/pixel	
Pixel format	2x2	67x67	167x167	pixels	
Subapertures across pupil		1	2	N/A	1

Notes:

1. LOWFS has a 2x2 Shack Hartmann mode (1 sensor) and a single subaperture tracking mode.

If the LOWFS system is implemented with a large field of view as assumed above, then the requirements on the acquisition camera can be relaxed. However, as mentioned in section 6.1, the telescope pointing error even for relatively short moves is of the order of a few arc seconds. So the acquisition directly to the LOWFS is probably not feasible, without at least one acquisition image and one pointing correction being sent to the telescope drive.

6.7. Interfaces to AO mechanism control and system software

The acquisition camera optical design has not been finalized but we anticipate that the acquisition camera will have filter wheels for photometric and possibly ND filters, a mechanism to focus the camera, and a means to trigger an exposure if a manual shutter is used. These mechanisms would be integrated into the AO optics bench control system software and hardware with the possible exception that a mechanical shutter might be integrated directly into the camera control software.

The current NGAO non real-time software design calls for the camera control functions such as reset, exposure time, readout, binning mode, etc. to be controlled by dedicated acquisition camera control software. Functions beyond simple camera control needed for acquisition include the following:

1. Basic processing of camera images such as background and pixel non-uniformity correction
2. Determining target locations with simple centroids, correlation algorithms, or functional fits
3. Identify field and target locations with pattern recognition algorithms
4. Provide information to the observer user interface; for example, an image with possible guide stars indicated by boxes
5. Provide pointing correction information to the telescope software and other AO subsystems, such as the LOWFS

It has not been determined at this time [29] which of these functions would reside in the acquisition camera control software, in a software layer directly above the acquisition camera control software, or in higher software layers such as the AO Sequencer or Observing Sequencer. See: *Keck Next Generation Adaptive Optics System Design Report, Non-Real-Time Controls* [29] for more details.

Table 8: Natural guide star acquisition detector specifications

	Format	Pixel Size	Plate Scale	Read Noise	Dark Current	Quantum Efficiency (%)					
	pixels	microns	"/pixel	e-	e-/pixel/sec	V	R	I	J	H	K
E2V CCD47-20 MAGIQ	1024x1024	13	0.176	10 (1)	0.5	85	75	40	N/A	N/A	N/A
deep-depletion CCD LBNL (2)	1024x1024	13	0.176	4	0.0028	75	90	92	N/A	N/A	N/A
Hawaii-1RG (Eng. grade)	1024x1024	18	0.176	20	0.1	N/A	N/A	N/A	60	60	65
Hawaii-2RG (Sci. grade)	2048x2048	18	0.088	5	0.1	N/A	N/A	N/A	60	60	65

Notes:

1. Using MAGIQ specifications, lower read noise possible with slower readout rate
2. Specs uncertain, devices of this size tested at Lawrence Berkley Laboratory, see Holland [30]

7. Conceptual design for NGS acquisition camera

7.1. Detector trade study: comparison of visible and near-IR acquisition sensors

The design team used the requirements discussed in the previous sections to develop possible detector systems that would be suitable for an NGS acquisition camera. The difficulties of field identification, in particular the need to distinguish tip tilt guide stars from binaries and field galaxies, motivated the selection of an IR sensitive detector as the basis for one design. The need for high sensitivity and a large field of view resulted in selection of a Hawaii-1RG detector with specifications similar to the AO SHARC camera. Although use of a science grade Hawaii 1RG or Hawaii 2RG array would provide better performance, the cost of a new array appears prohibitive compared to the cost of recycling the SHARC camera. We carry both a Hawaii-1RG engineering grade detector and a Hawaii-2RG science grade detector concept forward in our trade study. A commercial CCD, EEV47-20 (BT), was selected as less costly than an IR array and is identical to the current MAGIQ detectors. A deep-depletion CCD based on Lawrence Berkley Laboratory specifications [30] was selected as the third detector. It provides high quantum efficiency at wavelengths out to 1.1 micron, including all of the astronomical R and I bands. The LBNL array provides a compromise in performance between a near-IR camera and a commercial CCD.

Table 9: Star magnitude, color indices, and sky background assumed for the acquisition trade study

Band	Magnitude	Color Index	Sky Background (magnitude/arcsec^2)		
			Dark Sky	60 degrees from Full Moon	10 degrees from Full Moon
V	22	N/A	21.00	18.6	16.88
R	20.72	V-R=1.28	20.70	18.3	16.58
I	19.81	R-I=0.91	19.80	17.4	15.68
J	19.19	J-H=0.67	16.0	No change with lunar phase	
H	18.52	H-K=0.17	13.9		
K	18.25	V-K=3.65	13.0		

Table 10: Transmission assumptions for zenith observation with NGS acquisition camera

Transmission worksheet	CCD	Near-IR	Notes
Zenith angle	0	0	
Atmospheric transmission	0.891	0.891	Mauna Kea mean extinction 0.125 (mag./air mass)
Telescope primary	0.900	0.960	bare AL
Telescope secondary	0.900	0.960	bare AL
Telescope tertiary	0.900	0.960	bare AL
Window	0.922	0.922	4 surfaces at 0.98 each
K mirror M1	0.980	0.980	protected silver
K mirror M2	0.980	0.980	protected silver
K mirror M3	0.980	0.980	protected silver
OAP 1	0.980	0.980	protected silver
Fold	0.980	0.980	protected silver
DM	0.980	0.980	protected silver
OAP 2	0.980	0.980	protected silver
"post relay 1 dichroic"	0.950	0.950	dichroic
ACQ fold	0.980	0.980	protected silver
Focal reducer + windows	0.695	0.695	18 surfaces at 0.98 each
Total telescope	0.729	0.885	
Total NGAO	0.761	0.761	
Total acquisition camera	0.681	0.681	
Total optical transmission	0.378	0.458	
Total optical + atmospheric	0.337	0.409	

The specifications for the 4 detector concepts are shown in Table 8. The values in the table are representative values that the design team was able to get from various sources and are not vendor guaranteed specifications. The plate scales were determined by dividing the preliminary 180 arc second field of view (current design is 150 and the change has little effect on the results) of the first relay by the available pixels. This sampling appears reasonable for position determination (centroid, correlation, etc.) for seeing limited detectors in the visible such as the E2V and LBNL CCD. As discussed above in section 6.5, the level of AO correction at the acquisition camera will be modest at best; typical correction might be 0.2" FWHM in the near-IR bands. The Hawaii-2RG sampling is better matched to partial AO correction, while the Hawaii-1RG array sampling is better matched to seeing limited imaging in the near-IR. We evaluate both seeing limited and partial AO corrected performance for the two designs.

As a comparison study, we calculated the exposure time needed for each design concept to achieve an SNR of 10 when imaging an M0 spectral class star of V = 22. The chosen spectral type is typical of field stars at the galactic pole while the V magnitude is typical of the faintest [16] of the three tip tilt stars needed for the LOWFS assumed in the Extended Groth Strip science case. The assumed color indices and magnitudes in each astronomical band are given in Table 9, along with assumptions made about the sky background for various bands and moon phases. The IR band background assumed that the NGAO enclosure will be cooled and will have low emissivity. These values are consistent with assumptions made in the NGAO background study [31], the backgrounds used by Gemini telescope for Mauna Kea [32], and the measured backgrounds at the IRTF [33]. The lunar background is based on a model by Krisciuna and Schaefer [34]. The chosen values were used by the design studies for the MAGIQ guider. These values are the sky background 10 degrees away from the full moon and 60 degrees away from the full moon. The background 10 degrees from the full moon is a worst case for full moon observations. While the background 60 degrees from the full moon the is typical of worst case observation (few degrees away from the moon) made at lunar phases during first and last quarter, i.e. 5-10 days before or after the new moon.

Table 11: Performance comparison for various detectors for NGS acquisition camera

	Filter	Exposure time (sec.)[1]			Centroid error[2] (arc seconds)
		Dark Sky	60° Full Moon	10° Full Moon	
E2V CCD47-20 MAGIQ	R	2.4	10.0	46.4 (18)[3]	0.030
deep-depletion CCD LBNL	R	1.3	8.1	38.8 (8)[3]	0.030
Hawaii-1RG (Eng. grade.)	J plus H	0.80/0.20 (AO off/AO on)	Same	Same	0.024/0.012 (AO off/AO on)
Hawaii-2RG (Sci. grade)	J plus H	0.70/0.19 (AO off/AO on)	Same	Same	0.024/0.012 (AO off/AO on)

Notes:

1. M0 spectral class star, V = 22, see Table 9 for color indices and band magnitudes
2. Exposure time optimized to produce exactly a SNR = 10, needed for accurate centroid.
3. Values in brackets represent performance when an I filter is substituted for the R filter

The design team did not produce a detailed optical design for the acquisition camera optics, see section 7.2. However, given the pixel sizes of the detectors in Table 7, it is anticipated that some sort of focal reducer optics would be needed to reimage the desired field of view onto the detectors. We, somewhat pessimistically, assume that the optical system is made of 18 surfaces with transmission/reflectivity of 98 percent, including: multiple element lens, fold mirrors, dewar windows, and filters. The breakdown of the transmission from the atmosphere to the detector is given in Table 10. The column denoted CCD is used for astronomical V, R, and I band performance estimates. The column near-IR is used for astronomical bands J, H, and K. The NGAO transmission is estimated assuming that the position behind the optical selection mechanism ("post relay 1 dichroic") and in front of the LOWFS/d-IFS pickoff is selected, option 3 from section 6.3.

The design team used the assumptions outlined in the sections above to evaluate the image registration performance for the four detector concepts. The exposure time needed to reach an SNR of 10 was calculated. This SNR is appropriate for a good detection from which an accurate centroid can be determined. The centroid error was calculated using the formalism of King [19]. The Hawaii arrays were evaluated assuming both seeing limited (FWHM=0.4 arc seconds) and ground layer AO correction (FWHM=0.2 arc seconds). The CCD detectors were evaluated only for the seeing limited case (FHWM=0.5 arc seconds). The results are shown in Table 11. The Hawaii arrays performed well even in the seeing limited case. All detector concepts were comparable in dark sky conditions. The IR arrays do not suffer from an increase in sky background during bright time around the full moon but under these conditions, the CCD detectors do not perform as well. This disadvantage can be offset by shifting from the R to the I band. We evaluated this case for the CCD detectors and found that the exposure times at 10 degrees from the full moon were reduced from 46 to 18 seconds for the E2V detector and from 39 to 8 seconds for the LBNL detector. None of these exposure times is prohibitive when compared to the acquisition requirements for detector integration given in Table 4. The required exposure time can be as long as 20 seconds for worst case scenarios in Table 4.

This study has shown that any of the 4 detectors is sufficiently sensitive to meet the NGAO requirements. While our original study of acquisition detectors favored the use of the Hawaii-1RG and Hawaii-2RG arrays the information of sections 3, 4, and 5.2 leads us to conclude that optical detectors are just as effective for field identification. Switching to a CCD based detector would reduce costs and avoids the complications associated with a cryogenic NIR instrument. While the LNBL detector has advantages over the E2V CCD, especially when the bright sky background from the moon is an issue, these advantages must be weighed against the high cost and likely longer lead times when purchasing a CCD from a national laboratory as opposed to a commercial supplier. In addition, using the E2V CCD47-20, the same detector as the MAGIG guider upgrade at Keck, results in the ability to reuse extensive software developed for this project. Finally, since MAGIC is the standard guide camera configuration at Keck Observatory there is a spares inventory that will be extended as more installations are done, so NGAO will not need to provide its own spares.

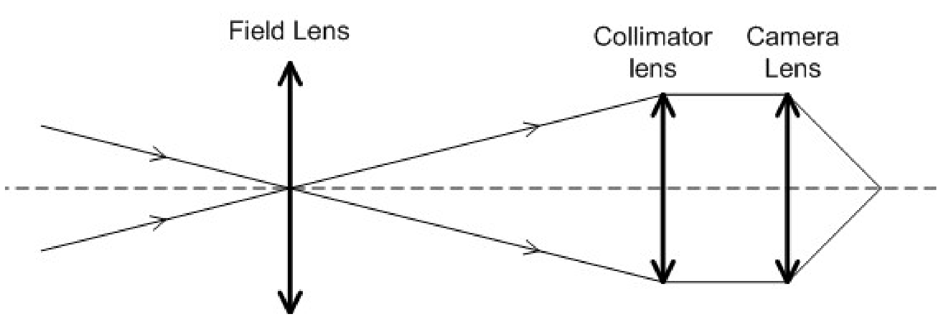
7.2. First order optical design

The pixel sizes for all proposed detectors are incompatible with final plate scales proposed in Table 8 and the plate scale of the main AO relay. The situation is easy rectified with a standard focal reducer that produces the desired plate scale. A thin lens layout of the required focal reducer is shown in Figure 1**Error! Reference source not found.**. Many other reimaging designs will also work. The field lens is chosen to image the exit pupil of the NGAO relay to a convenient size in the space between the collimator and camera lens. The function of the collimator is to produce a parallel beam between the collimator lens and the camera lens for filters and, in the case of a NIR detector, a cold pupil stop. The camera lens focal length is chosen to produce the desired final plate scale on the detector. The design is shown as refractive in **Error! Reference source not found.** although nothing at this level precludes using a reflective design that performs the same functions. Using paraxial optics and the thin lens approximation, the optical specifications are as given in Table 12. The camera f/# appears to be challenging for the visible detectors at f/1.4. This is fast for a commercial camera lens; some high-end lenses from Nikon are as fast as f/1.2. If the required performance cannot be met with such a lens, then a custom lens will probably be needed. The collimator and field lens can be relatively simple designs as they work at much slower f-numbers. In order to cover the full 150 arc second field of the AO relay, the field lens will need to be about 110 mm or larger in diameter. The designs are only a first order approximation and should be further developed using ray trace models of the full AO relay.

Table 12: Focal reducer optical specifications

Detectors	**Input plate scale** ("/mm)	**Detector plate scales** ("/pixel)	**Pixel sizes** (mm)	**Detector plate scale** ("/mm)	**Focal reducer camera lens** (f/#)
LLNL	1.3788	0.1758	13.00	13.52	1.39
E2V	1.3788	0.1758	13.00	13.52	1.39
Hawaii 1	1.3788	0.1758	18.00	9.77	1.93
Hawaii 2	1.3788	0.0879	18.00	4.88	3.86

Figure 1: Schematic representation of focal reducer.



7.3. Evaluation of acquisition detectors and recommendations

Based on the science acquisition scenarios from section 4 and situations where acquisition will be problematic given at the end of section 2, the design team evaluated the relative merits of a visible or near-IR sensor. We summarized our evaluation of the two detector types in Table 13. For these cases, a visible sensor is competitive with the more expensive NIR detectors. This conclusion is based on the following assumptions:

- LOWFS will have more than 2x2 pixels and is able to diagnose problems with faint galaxies and close double stars itself.
- Sloan Digital Sky Survey (SDSS) is complete to V = 22 and available at Keck.
- The LOWFS only need to work on source of J = 19 (V = 22) or brighter.

Table 13: Detector evaluation for problematic acquisition cases

Issue	Visible sensor	IR sensor	Notes
ID field	Yes	Yes	Both detectors depend on catalog information to the same degree
Photometry	Yes, relative	Yes, relative	
Obscured region (Gal. cent., dark clouds)	Not a problem, see notes	Not a problem	Need catalog of nearby optical sources, 150" FOV is sufficient
Color effects	Not a problem, see notes	Not a problem, same color sensitivity as LOWFS	SDSS provides accurate photometry for visible, can extrapolate to NIR
Moonlight	Use I band	No effect in NIR	Small increase in overhead for visible
Twilight	Use I band	No effect in NIR	Small increase in overhead for visible
Double stars (LOWFS)	Minor problem, <5%	Minor problem, <5%	Expected AO correction is poor, LOWFS will need to diagnose
Galaxies (LOWFS)	Minor problem, <5%	Minor problem, < 5%	Expected AO correction is poor, LOWFS will need to diagnose
Pre observing information	Use catalog	Use catalog	Backup is diffraction limited image of FOV (ACS, WFPC2, JWST, or Keck I LGSAO)
Quick response mode	Limited by completeness fraction in visible catalogs, leading possibly to some uncertainty in field ID	Limited by lower completeness fraction in NIR catalogs, leading possibly to larger uncertainty in field ID	No catalog backup in regions outside SDSS
Color effect/combined with high proper motion	Problematic	Easy to diagnose	

8. Single acquisition camera for LGS and NGS

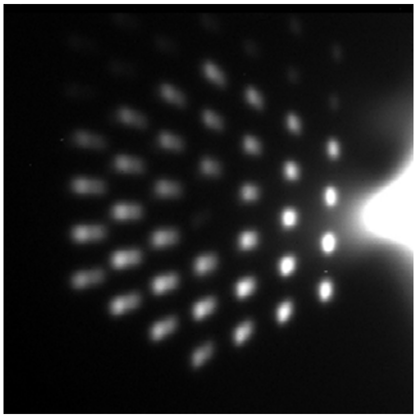
The current NGAO optical design [25] has locations for two acquisition cameras one for NGS and the other of LGS. The design was originally proposed to support the use of a NIR acquisition camera which was though to be superior for acquisition of NGS on the low order wavefront sensor. The results of sections 3, 4, 5.2, 7.1, and 7.3 have shown that a CCD is competitive with a NIR detector for this task. The CCD is now favored because of the lower cost and easy of operation and maintenance compared to a specialized NIR detector. The negative impact of this design choice is the present coatings for the "post relay 1 dichroic" may not allow wavelengths less than 1.0 μm to be transmitted into the acquisition camera. One option is to modify the coatings another is to switch to the mirror for acquisition and then move to the appropriate dichroic before attempting to close the loop on the LOWFS. This option will likely place tighter restrictions on the repeatability of the "post relay 1 dichroic" mechanism. This option should not affect the DM-to-lenslet registration of the LGS wavefront sensor, as the laser light is removed from the beam with the "LGS dichroic".

Since the LGS dichroic will reflect some small fraction (~ 1%) of the light at 589 nm into the rest of the down stream optics the NGS acquisition camera is likely useable for LGS acquisition. The camera only needs to be placed on a translation stage along with the focal reducer optics of section 7.2 and moved approximately 25 cm backward on the optical bench to reach the LGS focus. A similar arrangement is provided with the current Keck AO system acquisition camera (ACAM). Using the same formalism as section 7.1 and assuming a 1% reflectivity of the LGS dichroic, the E2V CCD47-20 is able to image a visual magnitude 10 LGS with an SNR of greater than 90 in only a 1 second exposure. This calculation assumed a high Rayleigh sky background resulting from looking at off axis guide stars.

The current Keck AO system LGS pointing model is sufficiently accurate that the LGS acquisition mode of ACAM is only used at the start of the evening to check that the LGS pointing model offset are still valid. It is likely that the NGAO system will also only need to use the LGS acquisition camera at the start of the night. The laser acquisition camera can also be used to measure the LGS elongation and sodium layer structure by imaging the laser guide stars with the Keck primary un-stacked, see Figure 2, similar image could be acquired with the NGAO acquisition camera.

The conceptual design of the NGS acquisition camera can meet all the additional LGS requirements. We recommend that these systems be combined into one camera as outlined in this section. The requirements for the LGS acquisition camera are given Appendix B. The requirements will continue to evolve during subsequent phases of the NGAO project. Please consult the requirements database for the most up to date requirements.

Figure 2: Image of laser guide star with Keck telescope primary mirror unstacked,



9. Conclusion and recommendations

Based on the considerations outlined in the previous sections of this report, the authors recommend the following design for the NGS acquisition sensor:

- An E2V CCD 47-20, the same one used for the MAGIQ project at Keck
- Focal reducer with a plate scale between 0.18-0.14 arc seconds per pixel
- Locate the NGS acquisition sensor after the d-IFS/LOWFS optical selection mechanism
- Use a mirror in the "post relay 1 dichroic" selection mechanism and a second mirror to direct the beam into the acquisition camera.
- Use I band filter for acquisition during "bright time"
- Adapt the MAGIC software for NGAO where appropriate

Our understanding of the completeness and accuracy of available star catalogs was a major factor in selecting a visible detector over an IR detector. The status of the GSC-2 and SDSS catalogs should be verified. During the preliminary design phase, work on the acquisition camera will include refinement of the optical and mechanical design and integration into the overall AO system. The software for the acquisition tasks in sections 2, 5.8, 5.9, and 6.7 must be integrated with the software design for AO non real-time control and observation planning tools.

Risks in the NGS acquisition design include a reliance on star catalogs. Based on information gathered for this study the SDSS and GSC-2 catalogs appear sufficient for NGAO. Another risk area is the LOWFS design as discussed in section 6.6. The conclusions in this report assume that the LOWFS will have a field of view of a few arc seconds. If the LOWFS is required to have many fewer pixels, for example an IR quad cell is selected as the final detector, then the requirements for the NGS acquisition system will need to be tightened accordingly. In particular, telescope pointing errors for small may need to be refined if the LOWFS field of view is very small, see section 6.1 and 6.6.

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Appendix A: NGS Requirements

Acquisition capability
The AO acquisition system is responsible for the acquisition of natural stars for the low order natural guide star wavefront sensors (LOWFS) and other NGS wavefront sensors, laser guide stars for the laser guide star wavefront sensor (LGS WFS), and the acquisition of the science target on the science instrument. These acquisition tasks shall occur in an automatic fashion with a minimum of telescope operator input. The field shall be accurately identified with a high probability of detecting natural guide stars and astronomical targets.

Interface to AO non real-time control
AO non real time control shall be responsible for control of acquisition cameras, including selection of optics and setting the exposure time. AO control shall determine when acquisition is successful in an automatic fashion with limited operator oversight

Interface to observer planning tools
Acquisition software shall receive target information from the NGAO observer planning tools

Field of view
The NGS acquisition camera field of view shall be greater than or equal to 150 arc seconds

IR field Identification
The acquisition camera shall be capable of identify targets in the NIR wavelength bands between 1.0 and 2.5 microns. This may be accomplished by imaging sources in the near-IR (1.0-2.0 micron) or imaging sources in the visible (0.5-1.0 micron). In both cases use supplementary information about target locations from catalogs and surveys

Point source sensitivity
The acquisition cameras shall have a limiting magnitude of V=22 if it uses visible detectors (CCDs). The acquisition camera shall have a limiting magnitude of J=19 if it uses NIR detectors. For the purpose of acquisition the limiting magnitude is defined as achieving a SNR of great or equal to 10 in an exposure time of less than or equal to 10 s

Position accuracy
The random errors from measurement noise when determining source positions in an acquisition camera image shall be 0.050 arc seconds rms or less. Measurement noise includes fundamental noise the detection process such as photon noise in the source and sky background, it also includes noise sources such as readout noise and detector dark current. Errors in registering the detector to a know coordinate system are part of the registration accuracy requirement

Minimal time overheads
The NGS acquisition shall take less than 90 seconds for NGS V ~ 18-20, less than 50 seconds for NGS V < 17 with the goal of achieving less than 20 seconds for the brightest targets. This requirement includes time for telescope moves, camera exposure, and analysis.

Photometric imagery
Photometric error of 0.2 magnitudes under transparent conditions, in standard astronomical bands such as Johnson, UKIDDS, SDSS.

Registration accuracy
0.020 arc seconds rms, random error in determining positions of acquisition camera with respect to telescope optical axis. The registration accuracy between the sensors and the NGS acquisition camera must be documented to less than 0.02 arc sec over the entire field-of-view.

Diagnostics and troubleshooting tools
Report metrics for automatic acquisition and to aide observer decision making. Include manual override by astronomer or observing assistant

Data products
All acquisition images shall be stored on the NGAO data server. Images shall be in FITS file format and have standard FITS header information. The exact content of the header are TBD. The data product from the acquisition system and the information from available catalogs or literature shall be recorded in the same photometry system and with comparable spatial resolution.

Guiding mode
The NGS acquisition system shall offer the capability to be used as a guider for the Keck telescope.

Sky background limit
The acquisition system should be capable of working in conditions of high background such as at twilight and near a full moon. The background for these conditions are 16.88 magnitudes per square arc second in the V band (Johnson), 16.0 magnitudes per square arc second in the J band (Johnson) and 13.0 magnitudes per square arc second in the K band (Johnson). The acquisition camera can select appropriate filter to minimize background as need, but it must still meet the point source sensitivity requirement for V=22 magnitude M0 stars in the effective spectral of the sensor.

LOWFS field of view
LOWFS pickoff mirror shall provide a field of view shall be 2 to 5 arc seconds in diameter.

Telescope pointing
The telescope shall provide a pointing accuracy of 15 arc seconds rms and 30 arc seconds peak to valley after large telescope slews of 40 degrees in elevation and 5 hours in azimuth. The telescope shall be able to point with less than 0.5 arc second rms error (and 1 arc second peak to valley error) for any move of less than 30 arc seconds (which corresponds to the peak to valley value for telescope pointing after a large move).

Astronomical Catalogs
Keck observatory shall provide astronomical catalog to support NGAO. Exact catalogs are TBD but will likely include 2-MASS, GSC-2, SDSS, and USNO 1.0B.

Appendix B: LGS Requirements

Acquisition capability
The AO acquisition system is responsible for the acquisition of natural stars for the low order natural guide star wavefront sensors (LOWFS) and other NGS wavefront sensors, laser guide stars for the laser guide star wavefront sensor (LGS WFS), and the acquisition of the science target on the science instrument. These acquisition tasks shall occur in an automatic fashion with a minimum of telescope operator input. The field shall be accurately identified with a high probability of detecting natural guide stars and astronomical targets.

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Data products
All acquisition images shall be stored on the NGAO data server. Images shall be in FITS file format and have standard FITS header information. The exact content of the header are TBD. The data product from the acquisition system and the information from available catalogs or literature shall be recorded in the same photometry system and with comparable spatial resolution.

Track LGS range
The LGS acquisition camera shall be able to track the range of the sodium layer as the telescope points away from zenith. The range of the sodium layer corresponding to zenith angles of 0 to 70 degrees is 80-270 kilometers. This range also accommodates variations in the mean zenith height of sodium layer 80-100 km

LGS source sensitivity
The LGS acquisition camera shall be able to detect LGS flux level as low as 80 photons/s/cm^2 which is comparable to a visual magnitude star. The SNR of the detection shall be 50 or greater, in a 1 second exposure. The Rayleigh sky background is assumed to be 13 magnitudes per arc square arc second.

Telescope pointing
The telescope shall provide a pointing accuracy of 15 arc seconds rms and 30 arc seconds peak to valley after large telescope slews of 40 degrees in elevation and 5 hours in azimuth. The telescope shall be able to point with less than 0.5 arc second rms error (and 1 arc second peak to valley error) for any move of less than 30 arc seconds (which corresponds to the peak to valley value for telescope pointing after a large move).