Keck Adaptive Optics Note 554

Keck Next Generation Adaptive Optics System Passband Definitions

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1. Introduction

This note recommends definitions for the NGAO system passbands from the telescope f/15 focal plane to the AO output focal plane for the wide field instrument (deployable IFS) and near-IR tip/tilt sensors, and to the narrow field focal plane for the near-IR and visible wavelength instruments. It is understood that each instrument and the near-IR tip/tilt sensors will modify the AO system passbands with additional filters as required by their scientific and technical needs. Similar expectations are applied to the other sensors (TWFS, LOWFS, acquisition camera). The assumption is also made that the ultimate limit on the short wavelength end of the AO system passband will be set by the beamsplitter used to direct LGS light to the HOWFS.

2. Rationale

The full extent of the wavelength range over which NGAO is expected to operate is defined by the requirement to reach at least 700 nm at the short end of the range, and the requirement to support observations in the K band to at least 2.4 μm at the long end of the range. In addition, there is a goal requirement to reach the Hα line at ~656.3 nm, presumably with useful (>10% Strehl) and reasonable throughput.

Within the AO system passbands, instruments and other sensors will use filters to permit selection of the desired wavelengths, suppress unwanted light for spectroscopic order sorting, and limit effects of sky and telescope background, moonlight, etc. The approach taken here is to assert that the flexibility for making design decisions within these subsystems is maximized by avoiding AO system passbands that impose limitations on the available wavelength range by any more than what is imposed by the fundamental limits on the useful AO system passbands. These fundamental limits are defined by three elements: the atmospheric transmission, the reflectivity of the telescope mirrors (M1 through M3), and the characteristics of the detectors used in the instruments.

Based on this approach, AO system passbands are presented here in the context of these fundamental definitions. This allows narrower passband definitions to be the province of the instrument or other technical subsystem where a more precise or narrow definition is required.

The passbands recommended here are understood to not limit access to the wavelength ranges important to the NGAO science cases, but it should be noted that as the design of the AO system proceeds, technical reasons may arise that will modify these definitions. For example, a performance or cost/benefit trade off may result in limiting a passband, or imposing some additional passband definitions. When such issues arise, they will need to be considered carefully to ensure that any new limitations on the wavelengths accessible to science are compatible with the science requirements.

3. Passband Definitions

3.1 Atmospheric Transmission

Atmospheric transmission from 0.9 to 3.0 µm is based on a theoretical Mauna Kea atmospheric transmission spectrum generated using the ATRAN program (Lord 1992) at 1 airmass (0º zenith angle) with 1 mm of precipitable water vapor. Atmospheric transmission from 310 nm to 900 nm is based on Bèland et al. 1988. The author intends to replace this with data generated using the MODTRAN program (Berk et al. 1999) for the same conditions when time permits.

A graph of the atmospheric transmission is shown in Figure 1.

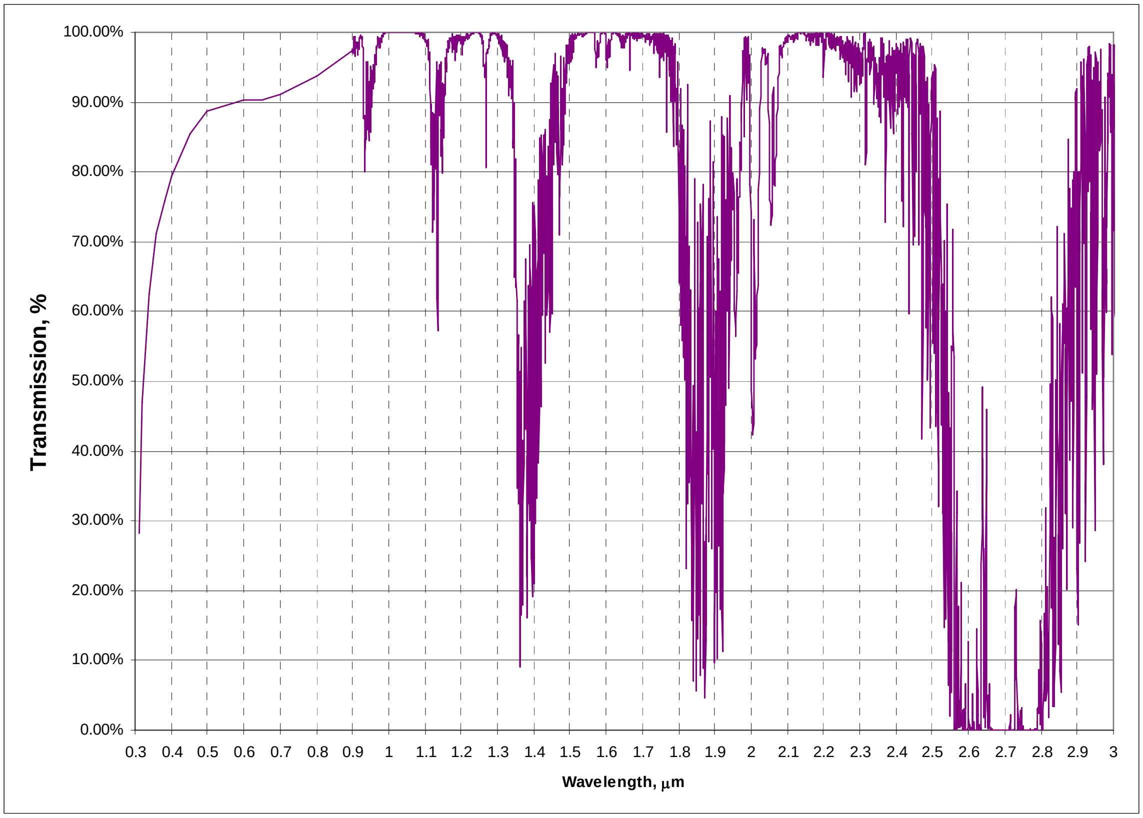

Figure 1: Atmospheric transmission

Figure 1 is a reminder of the reason why specific bands or "atmospheric windows" are defined for near-IR observing. A problem for photometric observations is that many absorption features in the near-IR are due to water vapor, and the variable character of these features makes it necessary to select observing passbands that exclude these absorption regions.

3.2 Telescope Transmission

The current Keck telescope mirror coatings are bare aluminum. These coatings are assumed to have the standard reflectivity described in Pettit 1934 and shown in Figure 2. The expected reflectance over the NGAO operating range is at least 85%, indicating that the telescope transmission is not expected to limit the NGAO passbands.

Figure 2: Keck telescope mirror coating reflectance vs. wavelength

3.3 Detector Wavelength Ranges

For instrumentation, the baseline detectors are HgCdTe infrared arrays for the near-IR (1.0 to 2.4 μm) and thick substrate high resistivity CCD detectors for the visible wavelengths to from ~650 to ~1000 nm.

Specifically the current instrument concepts employ the following detectors:

1. Teledyne Scientific & Imaging MBE processed substrate-removed HgCdTe Hawaii-2RG infrared arrays for the near-IR
2. Lawrence Berkeley National Laboratory (LBNL) fully depleted, high resistivity thick substrate 4096 x 4096 pixel CCDs for the visible wavelengths

These detectors offer state of the art QE performance over their design wavelength ranges. For the purposes of this discussion the portion of the QE curve that we are concerned with is the cut-off wavelength of the visible wavelength detector, and the cut-on and cut-off wavelengths of the near-IR detectors. Cut-on wavelength is defined here as the wavelength where the detector's QE rises to 50% of the mean detector QE. Cut-off wavelength is defined here as the wavelength where the detector's QE drops to 50% of the mean detector QE. The relevant portions of the two QE curves are shown in Figure 3. These data are based on Figer et al. 2004, and private communications regarding JWST NIRCAM detectors (McLean 2007) and LBNL detectors (Stover 2007).

The substrate-removed versions of the Hawaii-2RG have useful QE throughout our wavelength range of interest. However, these devices are considerably more expensive than the LBNL CCDs. They also require colder operating temperatures, and have longer readout times and higher read noise. It is also likely that instrument camera optical design will encounter some significant additional challenges if it is necessary to cover both the visible and near-IR wavelength ranges in one camera. For these reasons the use of CCDs for the visible wavelength range appears to be the best choice at this time.

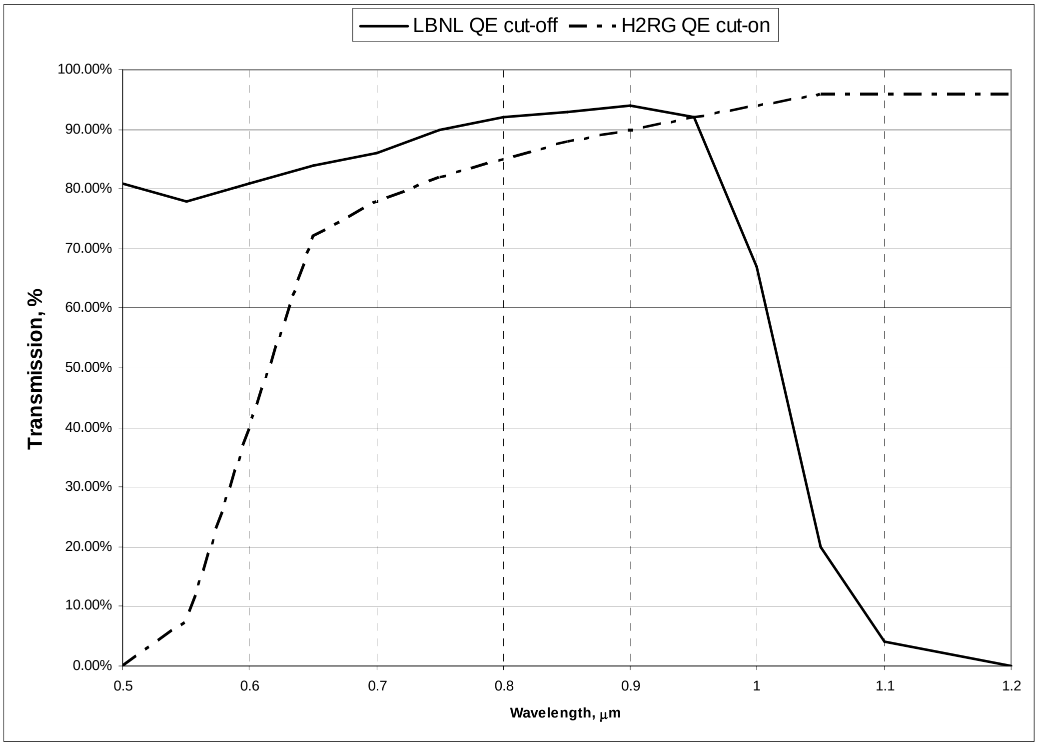

Figure 3: Detector QE cut-on and cut-off characteristics

The potential of the LBNL CCDs is illustrated in Figure 4. This figure shows the standard photometric visible wavelength r and i bands, and a photometric definition of the near-IR Y band (UKIDSS, Hewett et al. 2006). The QE of the LBNL CCD extends well beyond the i band, and has useful response into the middle of the near-IR Y band. This suggests that the long wavelength cut-off for the NGAO visible mode could be usefully extended for photometry by including both a photometric z' band and Y band, and for spectroscopy a passband that includes the ~920 to 970 nm wavelength range.

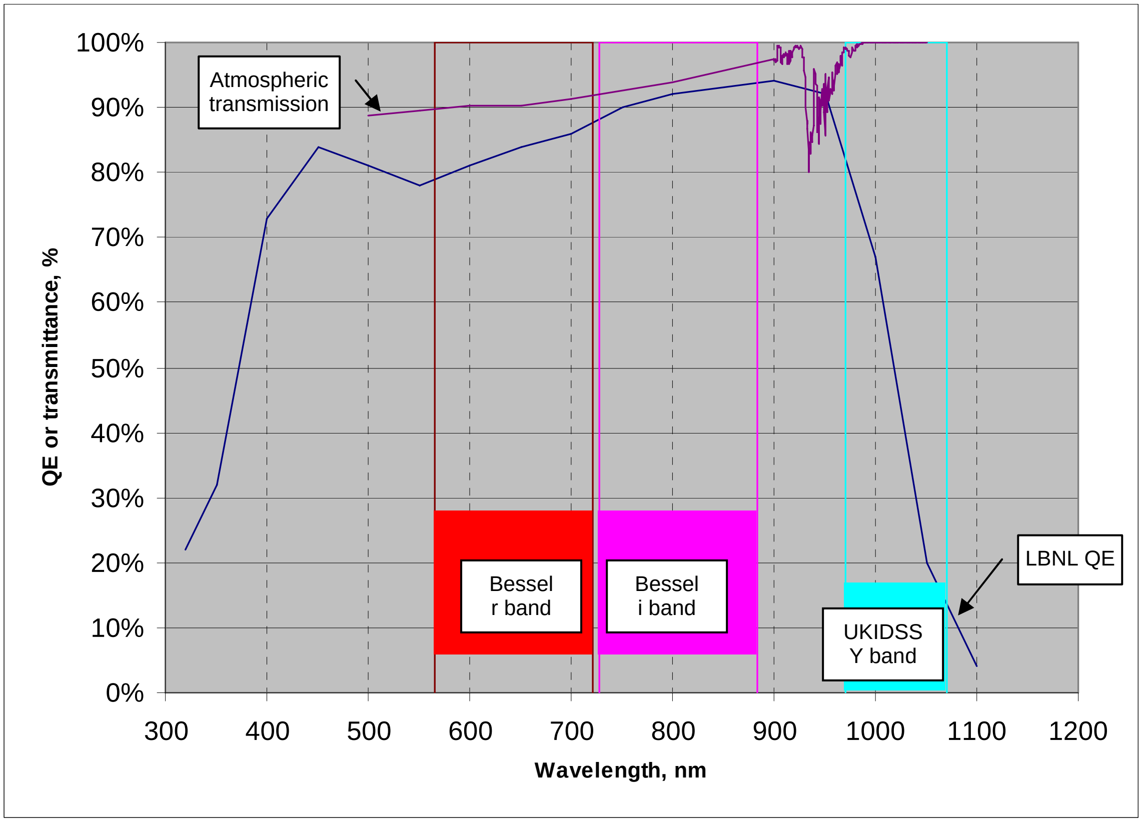

Figure 4: LBNL QE and standard photometric passbands

3.4 Standard Observing Bands

As noted earlier, the purpose of this note is not to define the observing bands for the NGAO instruments. However, a reference set of observing bands may be useful for various purposes in the design of the AO system, for example to estimate ensquared energy in a given observing band, or to estimate the performance of sensors that must share light with an instrument. For these purposes, observing passband definitions are included in Table 1 for both photometric and spectroscopic passbands.

It should also be noted that standard photometry in the r band will not be possible with NGAO because the wavelengths for the LGS light (~589 nm) are split off, and furthermore, in the best case the system is not expected to have significant Strehl below ~650 nm. Accordingly, a custom long pass r band filter is defined as a placeholder for this wavelength range.

3.5 System Passbands

The NGAO system passbands in terms of the cut-on and cut-off wavelengths are given in Table 1, along with reference photometric and spectroscopic observing passbands. For the NGAO passbands, the cut-on wavelength is defined as the highest wavelength at which the system should have at least 50% transmission, and the cut-off wavelength is defined as the lowest wavelength at which the system should have at least 50% transmission. It may be necessary to allow some margin below and above these wavelengths in order to avoid limiting the lower and upper cuts for the corresponding observing bands.

Passband name	**Cut-on λ (µm)**	**Cut-off λ (µm)**	**Notes**
NGAO Visible	**0.68 (0.62 goal)**	**1.07**	Goal is useful Strehl at Hα
NGAO rl	0.620	0.689	rl = "r band long", cut-on may be set higher depending on filter characteristics
NGAO i'	0.702	0.853	SDSS i' band
NGAO z'	0.818	0.922	SDSS z' band
NGAO z spec	0.855	1.050	Custom NGAO z band for spectroscopy
NGAO Near-IR	**0.97**	**2.40**	
NGAO Y	0.970	1.07	UKIDSS photometric
NGAO Y spec	0.970	1.120	
NGAO J	1.170	1.330	UKIDSS/Mauna Kea photometric
NGAO J spec	1.100	1.400	
NGAO H	1.490	1.780	UKIDSS/Mauna Kea photometric
NGAO H spec	1.475	1.825	
NGAO K	2.030	2.370	UKIDSS/Mauna Kea photometric
NGAO K spec	2.000	2.400	

Table 1: AO system passband characteristics

None of the reference observing passbands defined here are intended to preclude additional narrow band or other filter specifications for special purposes, and they may also not represent the final definitions adopted for the NGAO instruments, but it is believed that they are a good starting point for subsequent design choices.

The SDSS i' and z' bands are from the CFHT realizations of the SDSS filters (see the CFHT MegaCam web page). The UKIDSS and Mauna Kea photometric bands are from Hewett et al. 2006 and Tokunaga et al. 2002. The spectroscopic near-IR bands are from McLean 1997.

In all cases cut-on is defined as the wavelength where transmission has increased to 50% of the peak value for the corresponding filter, and cut-off is defined as the wavelength where transmission has decreased to 50% for the corresponding filter. Typical transmission and passband uniformity with actual filters is >90% and <5% respectively. The typical stop band transmission is <0.01% from 0.3 to >1.2 µm for the visible filters, and <0.01% from 0.3 to 2.6 µm for the near-IR filters.

The K band cut-off is shorter than what some sources may claim as the "end of K" or 2.45 µm. This is done for two reasons. First, as Figure 1 illustrates, atmospheric absorption begins to decline very steeply beyond 2.4 µm. Second, the thermal background is starting to increase very steeply at the same time. These effects rapidly reduce the possibilities for faint object spectroscopy, and passing this wavelength range adds to the difficulties in controlling thermal background, including that due to scattered radiation entering the optical path. By placing the long wavelength cut-off at 2.4 µm we avoid some problems with thermal background while at the same time not giving up a portion of the near-IR that is of importance to our faint object and sensitivity goals.

It should be noted that the definitions given here are for the technical characteristics of the limiting passband imposed by the AO system. That is, if these were actual filters, they are what would be measured using a calibrated detector and a narrow line width monochromator as a light source. They are not effective or "instrumental" wavelengths. Using a technical definition appears to be the most appropriate when evaluating performance parameters affected by the AO system such as transmittance and reflectance, and is also most appropriate when specifying coatings in support of the desired passband characteristics.

4. References

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