Keck Adaptive Optics Note 501

Keck Next Generation Adaptive Optics
Background and Transmission Budgets

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1. Background and Transmission Model

1.1 Description of background and transmission model

Our background and transmission models of the Keck NGAO system are based on the model of Herriot *et al.*[1] for the TMT NFIRAOS instrument. We begin with emission and transmission models of the night sky at high spectral resolution, tabulated for Mauna Kea from several sources[2] on the Gemini Observatory web pages. We then numerically propagate this spectrum through the telescope and AO system, multiplying the emission and transmission spectra by the reflectivity or transmission of each optical surface, and adding to the emission spectrum the thermal contribution of each surface.

Reflectivity and transmission spectra for standard optical materials were gathered from several sources, including the web sites of Denton Corp., and general references[3]. In cases where spectrally resolved data were not available, a scalar reflectivity and emissivity were used. All surfaces were initially assumed to be pristine, though this assumption is revisited in the next section.

The telescope and AO system were divided into three temperature zones. The first zone, whose temperature was assumed to be a constant 275.6 K (the annual average summit temperature[4]), includes the telescope optics, and any outer window into the AO system enclosure. The second zone, whose temperature can be varied, includes the inner pane of a double entrance window, all AO optics and dichroics, and the entrance window to the science instrument. The third temperature zone encompasses all instrument optics inside the instrument window.

It is important to note that this model predicts the performance of an optical system with no off-axis thermal contributions (eg. pupil stops exclude all warm surfaces such as secondary spiders and optics mounts).

1.2 Model validation and adjustment

Before evaluating the thermal background of candidate NGAO architectures, we compared model results for the current Keck 2 AO system to NIRC2 measurements of the sky background, and found the need for some adjustments. The science path of the "K2AO" architecture consists of three aluminized telescope mirrors, a K-mirror rotator (one silver and two aluminum surfaces), a 4-mirror AO relay, and a dichroic which transmits the infrared beam to the science camera entrance window (see Appendix A for the optical prescription used).

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[1] Herriot, G. *et al.* 2005, "NFIRAOS: Emissivity as a function of temperature & number of surfaces". TMT publication TMT.AOS.TEC.05.012.REL02.

[2] Krisciunas 1997, "Optical night-sky brightness at Mauna Ka over the course of a complete sunspot cycle", PASP 109, 1181-1188.

[3] Klocek, P. 1991, Handbook of Infrared Optical Materials (New York: Dekker).

[4] "Keck Telescope and Facility Instrument Guide", August 2002.

Transmission and background models for the K2AO architecture, with an AO enclosure temperature of 278.0 K, are shown in Figures 1 and 2. The sky brightness predicted by the "clean optics" model, in magnitudes per square arcsecond over standard filter bandpasses[5], is compared to measured NIRC2 values in Table 1. The predicted background is 0.24 to 0.31 magnitudes higher (darker) than that measured with NIRC2 in the K, L' and M_z bands, indicating an error in either the assumed temperature of the telescope and AO system or their emissivity.

An unrealistically high AO enclosure temperature of 283.0 K would be required to match the observed background with the initially assumed clean optical surfaces. We therefore choose instead to adjust the emissivity to match the observed background. In fact, adding just 0.8 % emissivity to all telescope and AO optical surfaces reproduces the observed NIRC2 background in K, L', and M_s. Since this seems to be a reasonable increase in emissivity due to dust and coating degradation over time, we choose to carry this conservative "real-world" correction forward as we model the background for NGAO candidate architectures.

Finally, we note that the average K band transmission of the adjusted Keck 2 AO system model is 86.4 % for the telescope and 70.2 % for the AO system, for a total transmission to NIRC2 of 60.6 %.

Filter	Average sky brightness (mag. arcsec^{-2})	NIRC2 measured background (mag. arcsec^{-2})	Initial Model background (mag. arcsec^{-2})	Adjusted model background (mag. arcsec^{-2})
J	16.01	*14.9*	15.90	15.89
H	13.78	13.6	13.72	13.71
K	14.91	12.6	12.91	12.63
L'	5.00	2.91	3.14	2.88
M_s	1.61	-0.12	0.12	-0.11

Table 1: Comparison of the Mauna Kea sky brightness, background measured with NIRC2, and model-predicted surface brightness for standard infrared filters. The adjusted model increased the emissivity of each optical surface by 0.8 %. The discrepant measured background value in the J band remains unexplained.

1.3 Instrument background requirement

Choosing the correct metric for evaluating thermal models of candidate AO architectures is somewhat subtle. The current requirement that *the AO system shall contribute <30% of the total background*[6], if interpreted as background at the science instrument, leads to the perverse result that AO systems with the lowest transmission must be cooled the least. This is because the background from the sky and telescope are viewed through the AO system, whose imperfect transmission (and colder temperature) reduces this background with each optical surface. Thus the requirement might more sensibly be specified in terms of the *unattenuated* sky plus telescope background, that which would today be measured by a detector placed at the Keck Nasmyth focus.

A second problem with the background requirement as stated above arises because the telescope itself is a major contributor to the thermal background seen by AO instruments. In fact, the telescope optics currently contribute over 10 times the background of the sky alone across a significant fraction of the K band (see Figure 3).

Given these two concerns with the background requirement as presently stated, we will reinterpret it as follows: **The total background seen by the NGAO instrument shall be less than 130% of the current unattenuated sky plus telescope background at 2209 nm and at a spectral resolution $\lambda/\Delta\lambda$ = 5000.** This wavelength was chosen to be near the center of the K band and free of atmospheric emission lines, and according to our model corresponds to a surface brightness requirement at the instrument focal plane of < 6.28 photons s^{-1} m^{-2} arcsec^{-2} nm^{-1} at 2209 nm.

[5] We used NIRC2 filter curves where available, otherwise published curves for Gemini NIRI filters.

[6] NGAO Architecture Requirements Summary, version 5 (July 2007).

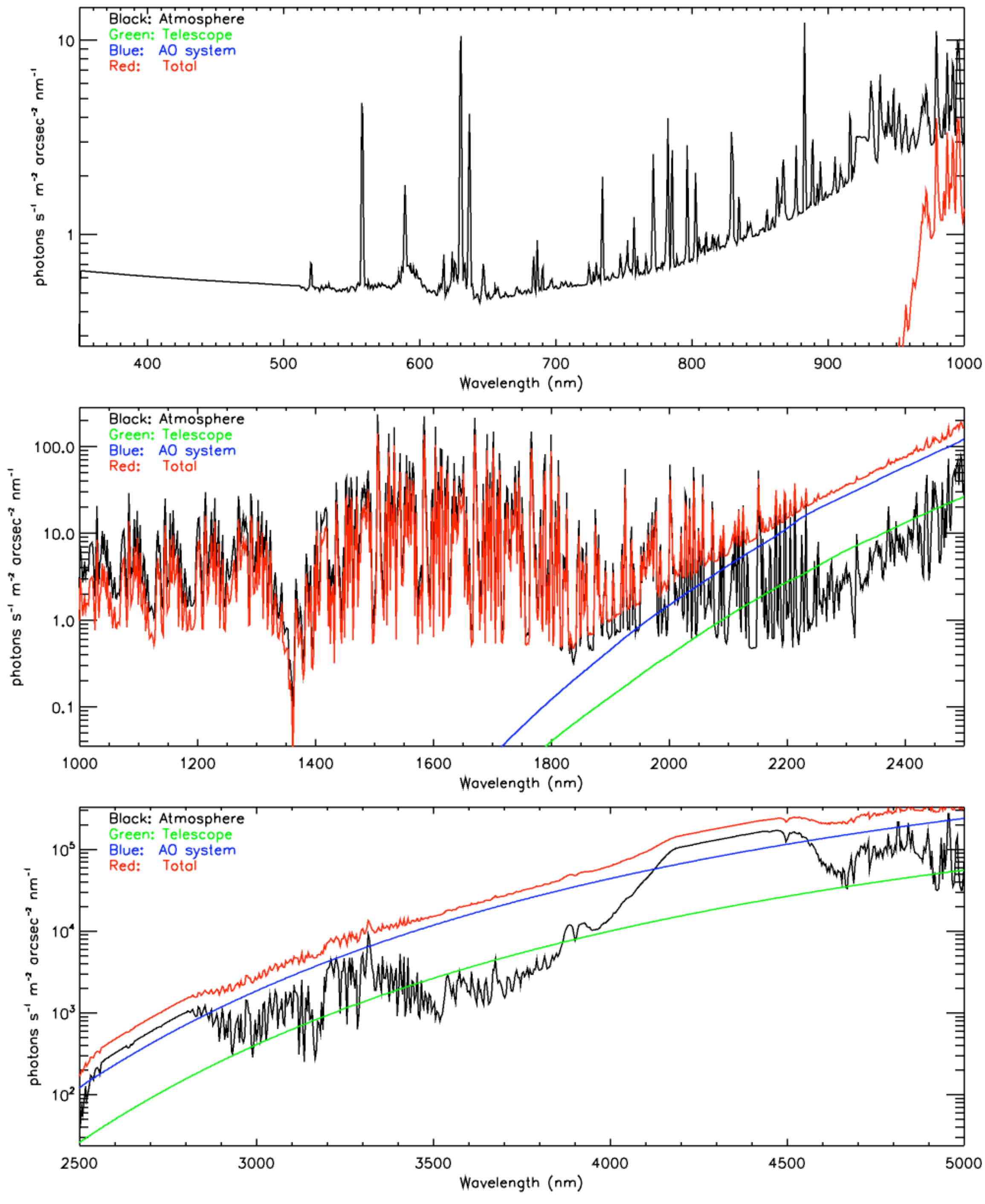

Figure 1: Background model for the science path of the Keck 2 AO system from 0.35 to 5 μm wavelength, at a spectral resolution of $\lambda/\Delta\lambda$=1000. The atmospheric background (unattenuated) is shown in black, that due only to the telescope (attenuated by the AO system) in green, that due only to the AO system in blue, and the total background at the science focal plane in red.

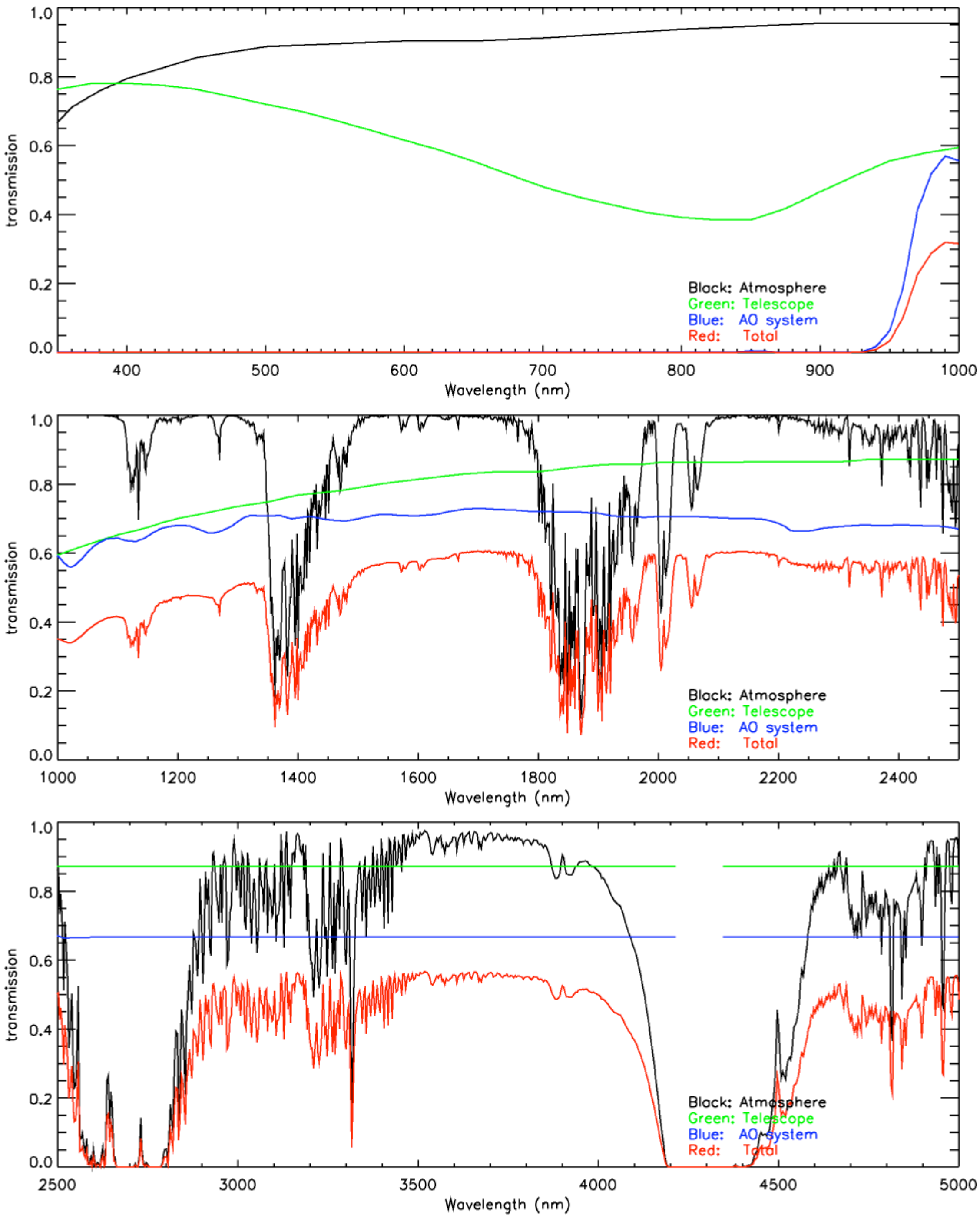

Figure 2: Transmission model for the science path of the Keck 2 AO system from 0.35 to 5 μm wavelength, displayed at a spectral resolution of $\lambda/\Delta\lambda=1000$. The transmission of the atmosphere alone is shown in black, that due only to the telescope and AO system in green and blue, and their product in red.

For comparison, the current Keck 2 AO system delivers a background of 15.5 photons s^{-1} m^{-2} $arcsec^{-2}$ nm^{-1} to the NIRC2 focal plane at 2209 nm, or 320% of the unattenuated telescope plus sky background. Meeting the requirement with no changes to the AO or telescope optics would require cooling the AO system to 262 K (though this is likely not possible without an additional window).

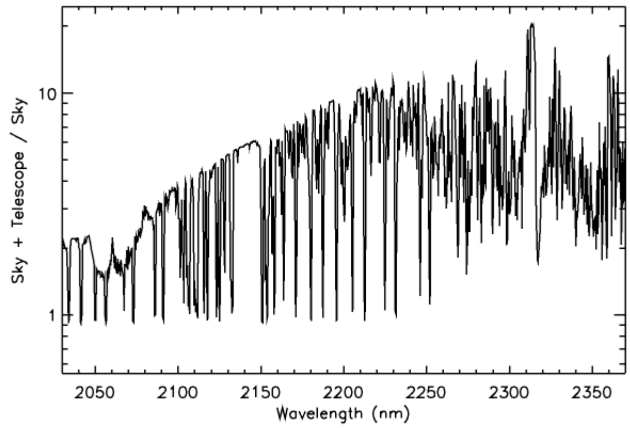

Figure 3: The ratio of the sky plus telescope background at nasmyth focus to the sky alone, as a function of wavelength in the K band, based on NIRC2 background measurements. Outside of the atmospheric emission lines, the telescope optics contribute 3 to 20 times as much background as the sky.

2 Results for NGAO candidate architectures

Results of thermal models for various NGAO architectures[7] are shown in Table 2, and discussed in more detail in the remainder of this section.

Architecture	AO K band transmission	AO temperature required to meet spec.	
		130%	150%
AM2, WF, cold OSM	77.2 %	273 K	> 278 K
AM2, WF, open OSM	78.0 %	262 K	267 K
AM2, NF	82.7 %	263 K	268 K
Split Relay, WF, cold OSM	70.4 %	264 K	270 K
Split Relay, WF, open OSM	71.1 %	261 K	264 K
Split Relay, NF	65.0 %	260 K	263 K
K1 Upgrade, WF, open OSM	54.3 %	260 K	263 K
K1 Upgrade, NF	60.7 %	260 K	263 K
Large Relay, WF, open OSM	52.5 %	260 K	263 K
Large Relay, NF	58.6 %	260 K	263 K
Cascade, WF, open OSM	56.2 %	260 K	263 K
Cascade, NF	52.7 %	259 K	262 K

Table 2: Predicted K band average transmission of AO system optics, and maximum AO enclosure temperatures which would meet 130% and 150% of sky+telescope background requirements (NF = narrow field; WF = wide field). Candidate architectures have been listed in oder of decreasing transmission and AO enclosure temperature.

[7] Velur, Viswa, 2007, "Surface counts for the five NGAO architectures", version 0.7.

2.1 AO enclosure temperature

The most important conclusion to draw from this study is that there is little distinction to be made between most of the NGAO candidate architectures with regards to the required AO enclosure temperatures. Only the AM2 architecture, and the Split Relay in its wide-field mode, allow enclosure temperatures significantly over 260 K. This is because the background at the AO foci is so dominated by a warm, emissive telescope (and to a lesser degree by the outer AO enclosure window, at approximately the same temperature) that additional cold (~260 K) optics do not significantly increase it.

While this is a somewhat dispiriting result, we should be encouraged that the temperatures required to meet the background specification are probably not too difficult to achieve in an observatory environment, and are not incompatible with maintenance tasks in the AO enclosure. For direct comparison to the Keck 2 AO system model, Figure 4 displays the model background for the Cascaded Relay architecture in its wide-field configuration, cooled to 260 K.

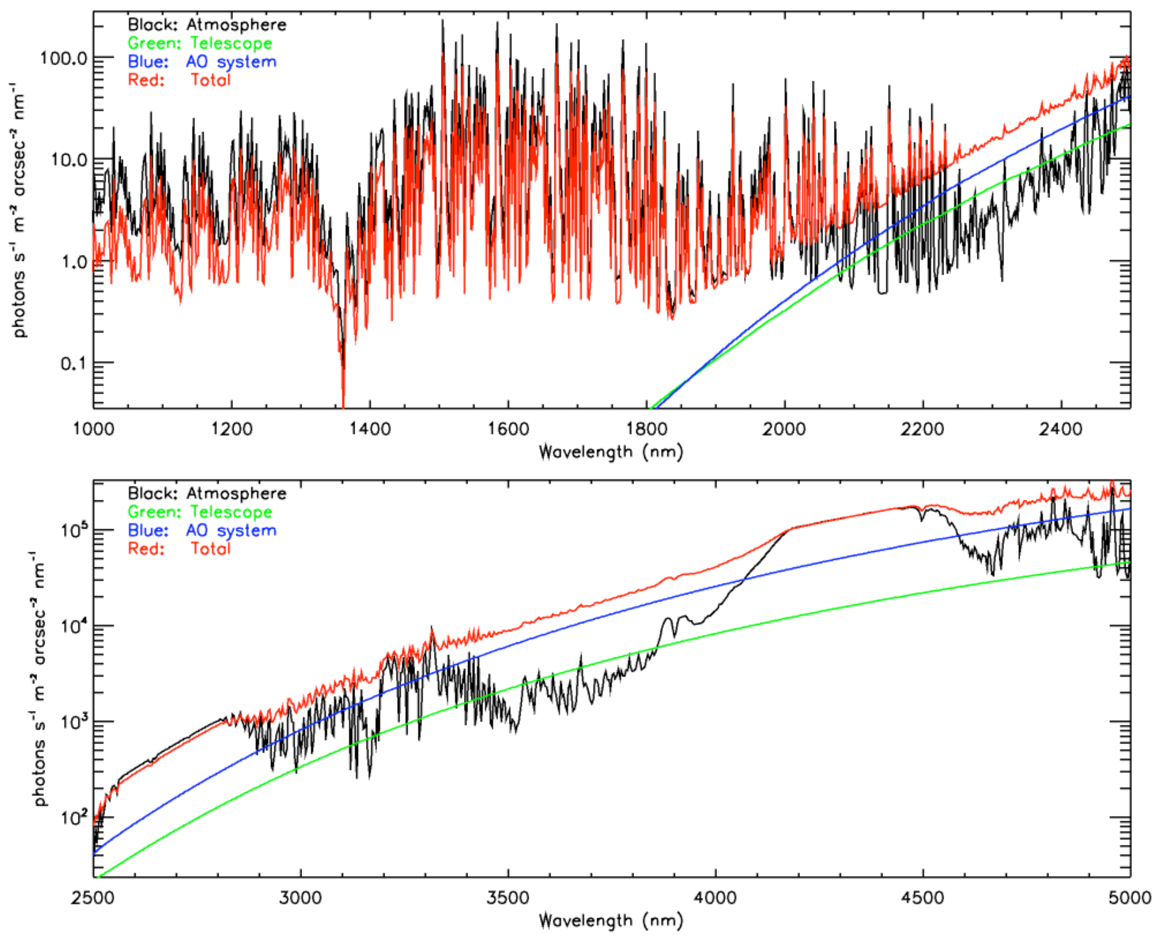

Figure 4: Background model for the Cascaded Relay candidate architecture in its wide-field ("open OSM") mode and cooled to 260.0 K, from 1 to 5 µm wavelength, at a spectral resolution of $\lambda/\Delta\lambda$=1000. The atmospheric background (unattenuated) is shown in black, that due only to the telescope (attenuated by the AO system) in green, that due only to the AO system in blue, and the total background at the science focal plane in red.

2.2 dNIRI object selection mechanism temperature

We also investigated the effect on the maximum permissibly AO enclosure temperature of two different configurations of the dNIRI object selection mechanism (OSM). The first configuration ("cold OSM" in Table 2), includes a window which thermally separates the OSM from the AO enclosure. The OSM volume is then assumed to be cooled to <260 K, at which point the OSM optics cease to contribute significantly to the background for the dNIRI instrument. This configuration reduces the number of optics at the AO enclosure temperature, and thus allows the temperature to be higher. In the second configuration ("open OSM"), all of the OSM optics are assumed to be at the AO enclosure temperature, with no window until the entrance to the dNIRI cryostat.

Only in the case of the AM2 candidate architecture does the "cold OSM" configuration make a significant difference, allowing the enclosure to be raised from 262 to 273 K in wide-field mode. However, since support of the narrow-field mode requires the enclosure temperature to be lowered to 263 K in any case, the balmy temperatures will not last! Thus there seems to be little argument for thermally isolating the dNIRI OSM from the AO enclosure, at the expense of one additional transmissive optics, if the enclosure temperature is to be lowered to ~260 K anyway.

2.3 AO system transmission

While there is little distinction between the maximum allowed temperatures of the various candidate architectures, the AO system transmission varies widely between them. The average transmission across the K band is given in Table 2, including all optics from the AO enclosure entrance window to the entrance window of the instrument cryostat. In the case of dNIRI, this includes the OSM optics and any entrance window to the OSM volume. The AO system K band transmission varies from a high of 82.7 % for the AM2 architecture in narrow-field mode, to a low of 52.5 % for the large relay in wide-field mode. The least transmissive narrow-field architecture is the cascaded relay, at 52.7 %. These values should be multiplied by an average telescope transmission of 86.4 % in the K band to get the total transmission to the science instrument (not including the sky).

3 Implications For Telescope Mirror Coatings

While the contribution of the AO system to near-infrared science instrument backgrounds can be limited to a small fraction of the total by cooling the AO enclosure to ~260 K, the total background emission is nevertheless elevated above the sky-only background by a factor of >10 across most of the K band. Since cooling the telescope below the ambient temperature does not appear to be a viable option, we consider here the possible benefits of lower emissivity telescope mirror coatings.

If a single aluminum telescope surface (eg. the tertiary mirror) were replaced with one coated with protected gold, the sky background at the nasmyth focal plane would be reduced by 17%. However, due to the background and transmission of the AO optics, the effect at the AO foci is significantly smaller. In the narrow-field mode of the Cascaded Relay, for example, the background surface brightness at 2209 nm would be reduced by 9%, which could allow the AO enclosure temperature to be raised just 2.0 K (to 262.4 K) while still meeting the 130% specification. Two gold surface would only allow the temperature to be raised a total of 3.8 K. Even a fully gold-coated telescope would not allow the Cascaded Relay architecture to meet the background requirements at ambient temperatures.

Candidate architectures with fewer optical surfaces do increase the effect of improving telescope mirror coatings. However, only in the case of the AM2 architecture can a fully gold-coated telescope be combined with an ambient (275.6 K) AO enclosure while still meeting the instrument background requirement. Thus, while lower emissivity telescope mirror coatings would clearly be beneficial to the performance of AO instruments in other architecures, they cannot eliminate the need for a cold AO enclosure. Furthermore, reducing the enclosure temperature by just a few degrees will have as large an effect on the AO instrument background as the coatings changes described here.

4 Conclusions

Having recast the NGAO instrument background requirement in terms of a maximum background surface brightness in the K band, we find that all candidate NGAO architectures require cooling the AO enclosure to 259 to 263 K. At these temperatures, the instrument background is nearly insensitive to additional optical surfaces in the AO system, though these will significantly reduce the transmission to the instrument and thus the signal to noise ratio for background-limited observations. Finally, we have found that a reduction of the telescope mirror emissivity, though beneficial, cannot eliminate the need for a cooled AO enclosure except in the case of the AM2 architecture.

5 Appendix: AO System Architectures

The following tables describe the optical elements used in each model in this report. Column 1 describes the optical element (surface or bulk properties). Column 2 gives the material or coating. Column 3 indicates the thickness in meters (-1 = reflection, 0 = transmission through a surface). Column 4 indicates the temperature zone to which the element belongs.

5.1 Keck 2 AO system

NGAO_BKG data file: K2AO optical design

ID	MATERIAL	THICKNESS	T
Keck M1	aluminum	-1.00E+00	TEL
Keck M2	aluminum	-1.00E+00	TEL
Keck M3	aluminum	-1.00E+00	TEL
rotator M1	aluminum	-1.00E+00	AO
rotator M2	prosilver	-1.00E+00	AO
rotator M3	aluminum	-1.00E+00	AO
TTM	prosilver	-1.00E+00	AO
OAP1	prosilver	-1.00E+00	AO
DM	prosilver	-1.00E+00	AO
OAP2	prosilver	-1.00E+00	AO
IR Dich 1 S1	ir_dich_t	0.00E+00	AO
IR Dich 1 B	CaF2	1.50E-02	AO
IR Dich 1 S2	nir_ar	0.00E+00	AO
Inst win S1	nir_ar	0.00E+00	AO
Inst win B	CaF2	1.00E-02	AO

5.2 AM2 candidate architecture

5.2.1 Wide field configuration, open OSM

NGAO architecture: AM2, wide-field, open dNIRI OSM

ID	MATERIAL	THICKNESS	T
Keck M1	aluminum	-1.00E+00	TEL
Keck M2	aluminum	-1.00E+00	TEL
Keck M3	aluminum	-1.00E+00	TEL
AO win 1 S1	opt_ar	0.00E+00	TEL
AO win 1 B	sapphire	1.50E-02	TEL
AO win 1 S2	opt_ar	0.00E+00	AO
IR Dich S1	ir_dich_1r	-1.00E+00	AO
OSM mir 1	gold	-1.00E+00	AO
OSM mir 2	gold	-1.00E+00	AO
Doublt 1 S1	nir_ar	0.00E+00	AO
Doublt 1 B	infrasil	1.00E-02	AO
Doublt 1 S2	nir_ar	0.00E+00	AO
MEMS win S1	opt_ar	0.00E+00	AO
MEMS win B	infrasil	2.00E-03	AO
MEMS win S2	opt_ar	0.00E+00	AO
DM	gold	-1.00E+00	AO
MEMS win S2	opt_ar	0.00E+00	AO
MEMS win B	infrasil	2.00E-03	AO
MEMS win S1	opt_ar	0.00E+00	AO
Doublt 2 S1	nir_ar	0.00E+00	AO
Doublt 2 B	infrasil	1.00E-02	AO

5.2.2 Narrow field configuration

```
NGAO architecture: AM2, wide-field (LGS mode)
ID           MATERIAL     THICKNESS T
     Keck M1     aluminum -1.00E+00 TEL
     Keck M2     aluminum -1.00E+00 TEL
     Keck M3     aluminum -1.00E+00 TEL
 AO win 1 S1       opt_ar  0.00E+00 TEL
 AO win 1  B     sapphire  1.50E-02 TEL
 AO win 1 S1       opt_ar  0.00E+00 AO
 dNIRI BS S1       opt_ar  0.00E+00 AO
 dNIRI BS  B         CaF2  1.50E-02 AO
 dNIRI BS S2       opt_ar  0.00E+00 AO
  Na dich S1    na_dich_t  0.00E+00 AO
  Na dich  B         CaF2  1.50E-02 AO
  Na dich S2       opt_ar  0.00E+00 AO
   ADC P1 S1       nir_ar  0.00E+00 AO
   ADC P1  B     adcglass  1.50E-02 AO
   ADC P2  B     adcglass  1.50E-02 AO
   ADC P2 S2       nir_ar  0.00E+00 AO
   ADC P3 S1       nir_ar  0.00E+00 AO
   ADC P3  B     adcglass  1.50E-02 AO
   ADC P4  B     adcglass  1.50E-02 AO
   ADC P4 S2       nir_ar  0.00E+00 AO
 Inst win S1       nir_ar  0.00E+00 AO
  Inst win B     infrasil  1.00E-02 AO
```

5.3 Split Relay candidate architecture

5.3.1 Wide field configuration, open OSM

```
NGAO architecture: Split relay, wide field, open dNIRI OSM
ID           MATERIAL     THICKNESS T
     Keck M1     aluminum -1.00E+00 TEL
     Keck M2     aluminum -1.00E+00 TEL
     Keck M3     aluminum -1.00E+00 TEL
 AO win 1 S1       opt_ar  0.00E+00 TEL
 AO win 1  B     sapphire  1.50E-02 TEL
 AO win 1 S2       opt_ar  0.00E+00 AO
 AO win 2 S1       opt_ar  0.00E+00 AO
 AO win 2  B     sapphire  1.50E-02 AO
 AO win 2 S2       opt_ar  0.00E+00 AO
  IR Dich S1    ir_dich_r -1.00E+00 AO
   OSM mir 1         gold -1.00E+00 AO
   OSM mir 2         gold -1.00E+00 AO
 Doublt 1 S1       nir_ar  0.00E+00 AO
 Doublt 1  B     infrasil  1.00E-02 AO
 Doublt 1 S2       nir_ar  0.00E+00 AO
 MEMS win S1       opt_ar  0.00E+00 AO
 MEMS win  B     infrasil  2.00E-03 AO
 MEMS win S2       opt_ar  0.00E+00 AO
          DM         gold -1.00E+00 AO
 MEMS win S2       opt_ar  0.00E+00 AO
 MEMS win  B     infrasil  2.00E-03 AO
 MEMS win S1       opt_ar  0.00E+00 AO
 Doublt 2 S1       nir_ar  0.00E+00 AO
```

```
 Doublt 2  B     infrasil  1.00E-02 AO
 Doublt 2 S2       nir_ar  0.00E+00 AO
 Inst win S1       nir_ar  0.00E+00 AO
 Inst win  B     infrasil  1.00E-02 AO
```

5.3.2 Narrow field configuration

```
NGAO architecture: Split relay, narrow-field (LGS mode)
ID           MATERIAL     THICKNESS T
     Keck M1     aluminum -1.00E+00 TEL
     Keck M2     aluminum -1.00E+00 TEL
     Keck M3     aluminum -1.00E+00 TEL
 AO win 1 S1       opt_ar  0.00E+00 TEL
 AO win 1  B     sapphire  1.50E-02 TEL
 AO win 1 S2       opt_ar  0.00E+00 AO
 AO win 2 S1       opt_ar  0.00E+00 AO
 AO win 2  B     sapphire  1.50E-02 AO
 AO win 2 S2       opt_ar  0.00E+00 AO
 dNIRI BS S1       opt_ar  0.00E+00 AO
 dNIRI BS  B         CaF2  1.50E-02 AO
 dNIRI BS S2       opt_ar  0.00E+00 AO
  Na dich S1    na_dich_t  0.00E+00 AO
  Na dich  B         CaF2  1.50E-02 AO
  Na dich S2       opt_ar  0.00E+00 AO
        OAP1    prosilver -1.00E+00 AO
  rotator M1     aluminum -1.00E+00 AO
          DM    prosilver -1.00E+00 AO
  rotator M3     aluminum -1.00E+00 AO
        OAP2    prosilver -1.00E+00 AO
   ADC P1 S1       nir_ar  0.00E+00 AO
   ADC P1  B     adcglass  1.50E-02 AO
   ADC P2  B     adcglass  1.50E-02 AO
   ADC P2 S2       nir_ar  0.00E+00 AO
   ADC P3 S1       nir_ar  0.00E+00 AO
   ADC P3  B     adcglass  1.50E-02 AO
   ADC P4  B     adcglass  1.50E-02 AO
   ADC P4 S2       nir_ar  0.00E+00 AO
 Inst win S1       nir_ar  0.00E+00 AO
  Inst win B     infrasil  1.00E-02 AO
```

5.4 Large Relay candidate architecture

5.4.1 Wide field configuration, open OSM

```
NGAO architecture: Large relay, wide field, open dNIRI OSM
ID           MATERIAL     THICKNESS T
     Keck M1     aluminum -1.00E+00 TEL
     Keck M2     aluminum -1.00E+00 TEL
     Keck M3     aluminum -1.00E+00 TEL
 AO win 1 S1       opt_ar  0.00E+00 TEL
 AO win 1  B     sapphire  1.50E-02 TEL
 AO win 1 S2       opt_ar  0.00E+00 AO
 AO win 2 S1       opt_ar  0.00E+00 AO
 AO win 2  B     sapphire  1.50E-02 AO
 AO win 2 S2       opt_ar  0.00E+00 AO
  rotator M1     aluminum -1.00E+00 AO
```

```
  rotator M2    prosilver -1.00E+00 AO
  rotator M3     aluminum -1.00E+00 AO
        OAP1    prosilver -1.00E+00 AO
         DM1    prosilver -1.00E+00 AO
         DM2    prosilver -1.00E+00 AO
         TTM    prosilver -1.00E+00 AO
        OAP1    prosilver -1.00E+00 AO
  IR Dich S1    ir_dich_r -1.00E+00 AO
   OSM mir 1         gold -1.00E+00 AO
   OSM mir 2         gold -1.00E+00 AO
 Doublt 1 S1       nir_ar  0.00E+00 AO
 Doublt 1  B     infrasil  1.00E-02 AO
 Doublt 1 S2       nir_ar  0.00E+00 AO
 MEMS win S1       opt_ar  0.00E+00 AO
 MEMS win  B     infrasil  2.00E-03 AO
 MEMS win S2       opt_ar  0.00E+00 AO
          DM         gold -1.00E+00 AO
 MEMS win S2       opt_ar  0.00E+00 AO
 MEMS win  B     infrasil  2.00E-03 AO
 MEMS win S1       opt_ar  0.00E+00 AO
 Doublt 2 S1       nir_ar  0.00E+00 AO
 Doublt 2  B     infrasil  1.00E-02 AO
 Doublt 2 S2       nir_ar  0.00E+00 AO
 Inst win S1       nir_ar  0.00E+00 AO
 Inst win  B     infrasil  1.00E-02 AO
```

5.4.2 Narrow field configuration

```
NGAO architecture: Large relay, narrow field (LGS mode)
ID           MATERIAL     THICKNESS T
     Keck M1     aluminum -1.00E+00 TEL
     Keck M2     aluminum -1.00E+00 TEL
     Keck M3     aluminum -1.00E+00 TEL
 AO win 1 S1       opt_ar  0.00E+00 TEL
 AO win 1  B     sapphire  1.50E-02 TEL
 AO win 1 S2       opt_ar  0.00E+00 AO
 AO win 2 S1       opt_ar  0.00E+00 AO
 AO win 2  B     sapphire  1.50E-02 AO
 AO win 2 S2       opt_ar  0.00E+00 AO
  rotator M1     aluminum -1.00E+00 AO
  rotator M2    prosilver -1.00E+00 AO
  rotator M3     aluminum -1.00E+00 AO
        OAP1    prosilver -1.00E+00 AO
         DM1    prosilver -1.00E+00 AO
         DM2    prosilver -1.00E+00 AO
         TTM    prosilver -1.00E+00 AO
        OAP1    prosilver -1.00E+00 AO
 dNIRI BS S1       opt_ar  0.00E+00 AO
 dNIRI BS  B         CaF2  1.50E-02 AO
 dNIRI BS S2       opt_ar  0.00E+00 AO
  Na dich S1    na_dich_t  0.00E+00 AO
  Na dich  B         CaF2  1.50E-02 AO
  Na dich S2       opt_ar  0.00E+00 AO
   ADC P1 S1       nir_ar  0.00E+00 AO
   ADC P1  B     adcglass  1.50E-02 AO
```

```
   ADC P2  B     adcglass  1.50E-02 AO
   ADC P2 S2       nir_ar  0.00E+00 AO
   ADC P3 S1       nir_ar  0.00E+00 AO
   ADC P3  B     adcglass  1.50E-02 AO
   ADC P4  B     adcglass  1.50E-02 AO
   ADC P4 S2       nir_ar  0.00E+00 AO
 Inst win S1       nir_ar  0.00E+00 AO
  Inst win B     infrasil  1.00E-02 AO
```

5.5 Keck 1 Upgrade candidate architecture

5.5.1 Wide field configuration, open OSM

```
NGAO architecture: Keck 1 upgrade, wide field, open dNIRI OSM
ID           MATERIAL     THICKNESS T
     Keck M1     aluminum -1.00E+00 TEL
     Keck M2     aluminum -1.00E+00 TEL
     Keck M3     aluminum -1.00E+00 TEL
 AO win 1 S1       opt_ar  0.00E+00 TEL
 AO win 1  B     sapphire  1.50E-02 TEL
 AO win 1 S2       opt_ar  0.00E+00 AO
 AO win 2 S1       opt_ar  0.00E+00 AO
 AO win 2  B     sapphire  1.50E-02 AO
 AO win 2 S2       opt_ar  0.00E+00 AO
  rotator M1     aluminum -1.00E+00 AO
  rotator M2    prosilver -1.00E+00 AO
  rotator M3     aluminum -1.00E+00 AO
         TTM    prosilver -1.00E+00 AO
        OAP1    prosilver -1.00E+00 AO
          DM    prosilver -1.00E+00 AO
        OAP2    prosilver -1.00E+00 AO
  IR Dich S1    ir_dich_r -1.00E+00 AO
   OSM mir 1         gold -1.00E+00 AO
   OSM mir 2         gold -1.00E+00 AO
 Doublt 1 S1       nir_ar  0.00E+00 AO
 Doublt 1  B     infrasil  1.00E-02 AO
 Doublt 1 S2       nir_ar  0.00E+00 AO
 MEMS win S1       opt_ar  0.00E+00 AO
 MEMS win  B     infrasil  2.00E-03 AO
 MEMS win S2       opt_ar  0.00E+00 AO
          DM         gold -1.00E+00 AO
 MEMS win S2       opt_ar  0.00E+00 AO
 MEMS win  B     infrasil  2.00E-03 AO
 MEMS win S1       opt_ar  0.00E+00 AO
 Doublt 2 S1       nir_ar  0.00E+00 AO
 Doublt 2  B     infrasil  1.00E-02 AO
 Doublt 2 S2       nir_ar  0.00E+00 AO
 Inst win S1       nir_ar  0.00E+00 AO
 Inst win  B     infrasil  1.00E-02 AO
```

5.5.2 Narrow field configuration

```
NGAO architecture: Keck 1 upgrade, narrow field (LGS mode)
ID           MATERIAL     THICKNESS T
     Keck M1     aluminum -1.00E+00 TEL
     Keck M2     aluminum -1.00E+00 TEL
```

```
     Keck M3     aluminum -1.00E+00 TEL
 AO win 1 S1       opt_ar  0.00E+00 TEL
 AO win 1  B     sapphire  1.50E-02 TEL
 AO win 1 S2       opt_ar  0.00E+00 AO
 AO win 2 S1       opt_ar  0.00E+00 AO
 AO win 2  B     sapphire  1.50E-02 AO
 AO win 2 S2       opt_ar  0.00E+00 AO
  rotator M1     aluminum -1.00E+00 AO
  rotator M2    prosilver -1.00E+00 AO
  rotator M3     aluminum -1.00E+00 AO
         TTM    prosilver -1.00E+00 AO
        OAP1    prosilver -1.00E+00 AO
          DM    prosilver -1.00E+00 AO
        OAP2    prosilver -1.00E+00 AO
 dNIRI BS S1       opt_ar  0.00E+00 AO
 dNIRI BS  B         CaF2  1.50E-02 AO
 dNIRI BS S2       opt_ar  0.00E+00 AO
  Na dich S1    na_dich_t  0.00E+00 AO
  Na dich  B         CaF2  1.50E-02 AO
  Na dich S2       opt_ar  0.00E+00 AO
   ADC P1 S1       nir_ar  0.00E+00 AO
   ADC P1  B     adcglass  1.50E-02 AO
   ADC P2  B     adcglass  1.50E-02 AO
   ADC P2 S2       nir_ar  0.00E+00 AO
   ADC P3 S1       nir_ar  0.00E+00 AO
   ADC P3  B     adcglass  1.50E-02 AO
   ADC P4  B     adcglass  1.50E-02 AO
   ADC P4 S2       nir_ar  0.00E+00 AO
 Inst win S1       nir_ar  0.00E+00 AO
  Inst win B     infrasil  1.00E-02 AO
```

5.6 Cascaded Relay candidate architecture

5.6.1 Wide field configuration, open OSM

```
NGAO architecture: Cascaded relay, wide field, open dNIRI OSM
ID           MATERIAL     THICKNESS T
     Keck M1     aluminum -1.00E+00 TEL
     Keck M2     aluminum -1.00E+00 TEL
     Keck M3     aluminum -1.00E+00 TEL
 AO win 1 S1       opt_ar  0.00E+00 TEL
 AO win 1  B     sapphire  1.50E-02 TEL
 AO win 1 S2       opt_ar  0.00E+00 AO
 AO win 2 S1       opt_ar  0.00E+00 AO
 AO win 2  B     sapphire  1.50E-02 AO
 AO win 2 S2       opt_ar  0.00E+00 AO
  rotator M1     aluminum -1.00E+00 AO
  rotator M2    prosilver -1.00E+00 AO
  rotator M3     aluminum -1.00E+00 AO
        OAP1    prosilver -1.00E+00 AO
          DM    prosilver -1.00E+00 AO
        OAP2    prosilver -1.00E+00 AO
  IR Dich S1    ir_dich_r -1.00E+00 AO
   OSM mir 1         gold -1.00E+00 AO
   OSM mir 2         gold -1.00E+00 AO
```

```
 Doublt 1 S1       nir_ar  0.00E+00 AO
 Doublt 1  B     infrasil  1.00E-02 AO
 Doublt 1 S2       nir_ar  0.00E+00 AO
 MEMS win S1       opt_ar  0.00E+00 AO
 MEMS win  B     infrasil  2.00E-03 AO
 MEMS win S2       opt_ar  0.00E+00 AO
          DM         gold -1.00E+00 AO
 MEMS win S2       opt_ar  0.00E+00 AO
 MEMS win  B     infrasil  2.00E-03 AO
 MEMS win S1       opt_ar  0.00E+00 AO
 Doublt 2 S1       nir_ar  0.00E+00 AO
 Doublt 2  B     infrasil  1.00E-02 AO
 Doublt 2 S2       nir_ar  0.00E+00 AO
 Inst win S1       nir_ar  0.00E+00 AO
 Inst win  B     infrasil  1.00E-02 AO
```

5.6.2 Narrow field configuration

```
NGAO architecture: Cascaded relay, narrow field (LGS mode)
ID            MATERIAL     THICKNESS T
     Keck M1     aluminum -1.00E+00 TEL
     Keck M2     aluminum -1.00E+00 TEL
     Keck M3     aluminum -1.00E+00 TEL
 AO win 1 S1       opt_ar  0.00E+00 TEL
 AO win 1  B     sapphire  1.50E-02 TEL
 AO win 1 S2       opt_ar  0.00E+00 AO
 AO win 2 S1       opt_ar  0.00E+00 AO
 AO win 2  B     sapphire  1.50E-02 AO
 AO win 2 S2       opt_ar  0.00E+00 AO
  rotator M1     aluminum -1.00E+00 AO
  rotator M2    prosilver -1.00E+00 AO
  rotator M3     aluminum -1.00E+00 AO
        OAP1    prosilver -1.00E+00 AO
          DM    prosilver -1.00E+00 AO
        OAP2    prosilver -1.00E+00 AO
 dNIRI BS S1       opt_ar  0.00E+00 AO
 dNIRI BS  B         CaF2  1.50E-02 AO
 dNIRI BS S2       opt_ar  0.00E+00 AO
  Na dich S1    na_dich_t  0.00E+00 AO
  Na dich  B         CaF2  1.50E-02 AO
  Na dich S2       opt_ar  0.00E+00 AO
        OAP3    prosilver -1.00E+00 AO
 MEMS win S1       opt_ar  0.00E+00 AO
 MEMS win  B     infrasil  2.00E-03 AO
 MEMS win S2       opt_ar  0.00E+00 AO
          DM    prosilver -1.00E+00 AO
 MEMS win S2       opt_ar  0.00E+00 AO
 MEMS win  B     infrasil  2.00E-03 AO
 MEMS win S1       opt_ar  0.00E+00 AO
   ADC P1 S1       nir_ar  0.00E+00 AO
   ADC P1  B     adcglass  1.50E-02 AO
   ADC P2  B     adcglass  1.50E-02 AO
   ADC P2 S2       nir_ar  0.00E+00 AO
   ADC P3 S1       nir_ar  0.00E+00 AO
   ADC P3  B     adcglass  1.50E-02 AO
```

ADC P4 B	adcglass	1.50E-02	AO
ADC P4 S2	nir_ar	0.00E+00	AO
OAP4	prosilver	-1.00E+00	AO
Inst win S1	nir_ar	0.00E+00	AO
Inst win B	infrasil	1.00E-02	AO