Thermal Infrared Sky Background for a High-Arctic Mountain Observatory

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Abstract
Nighttime zenith sky spectral brightness in the 3.3–20 µm wavelength region is reported for an observatory site nearby Eureka on Ellesmere Island in the Canadian High Arctic. Measurements are derived from an automated Fourier-transform spectrograph that operated there continuously over three consecutive winters. During that time, the median through the most transparent portion of the Q window was 460 Jy arcsec$^{-2}$, falling below 32 Jy arcsec$^{-2}$ in the N band, and to sub-Jansky levels by M and shortward, reaching only 36 mJy arcsec$^{-2}$ within L. Nearly six decades of twice-daily balloonsonde launches from Eureka, together with contemporaneous meteorological data plus a simple model, allows characterization of background stability and extrapolation into K band. This suggests that the study location has dark skies across the whole thermal infrared spectrum, typically sub-200 µJy arcsec$^{-2}$ at 2.4 µm. That background is comparable to South Pole and more than an order of magnitude less than estimates for the best temperate astronomical sites, all at much higher elevation. Considerations relevant to future facilities, including for polar transient surveys, are discussed.

Key words: site testing

1. Introduction
Coordinated efficient wide-field surveys spanning extended monitoring periods are needed to catch the shortest, faintest, and rarest transient phenomena. One such search is for the electromagnetic counterparts of binary black hole mergers now being detected via gravitational waves (Abbott et al. 2016). Multiwavelength follow-ups of these and neutron-star kilonovae are underway worldwide from the radio to the optical, as well as with X-rays and gamma-rays from space (e.g., Kasliwal et al. 2016). Viewing those sources in the thermal infrared is desirable, as they are less obscured by intervening dust. If viewed from a cold, high-latITUDE observatory they could provide both simultaneous coverage during seasonal dark periods together with low local background—including that from the telescope—which is expected to be a powerful combination (Yuan et al. 2013).

In winter, polar sites enjoy high clear sky fractions and typically lie inside encircling upper-atmospheric winds called polar vortices that isolate their frigid air, which soon desiccates. Furthermore, under continuous darkness for months, a radiative surface condition induces a strong and stable low-altitude thermal inversion, effectively trapping what little cloud cover persists; thin aerosol attenuation due primarily to suspended ice crystals know as “diamond dust” (Lawrence 2004; Steinbring et al. 2012). This stratified atmosphere provides excellent seeing when above surface effects on the central Antarctic plateau (Saunders et al. 2009, and references therein) and from the elevated terrain in the Arctic (Hickson et al. 2013; Steinbring et al. 2013). Therefore, the only significant remaining hindrance to potential infrared polar survey cadence and depth can be thermal emission of the atmosphere itself.

Near the Eureka weather station on Ellesmere Island, Canada, at 80° north latitude, sea-level air temperatures in mid-winter can reach −50°C and are typically −40°C to −30°C (reviewed in Steinbring et al. 2010). During the continuous night from October through February, a steep (positive) lapse rate of 10 to 20°C km$^{-1}$ is usually maintained. Thus, for the Polar Environment Atmospheric Research Laboratory (PEARL) adjacent to Eureka and at 600 m elevation above sea level (a.s.l.), the air temperature, between −30°C to −10°C, is almost always at its peak within the troposphere. Ellesmere Island has greater summits, topping 2600 m, although none of them match the Greenland icecap height of 2800 m. Analogously for the South Pole (90° S), also at 2800 m elevation, surface temperatures hover around −60°C in July rising to −40°C at 300 m above, close to the inversion peak. The central Antarctic glacial plateau reaches even higher at the other “Domes,” offering the most extreme nighttime surface air temperatures on Earth, at times surpassing −90°C for Dome A (80° S) and 4200 m elevation. Despite similar elevation, however, the highest temperate mountain sites are comparatively warm; for example, Maunakea (20° N, 4200 m a.s.l.) is typically near 0°C during winter nighttime, with diurnal variation often taking summit air temperatures above freezing during the day.

A thermal sky-emission model is developed here within a suitable range of atmospheric transmission, allowing a High Arctic mountain to be put into context with other polar and
mid-latitude sites. Data from balloon-borne radiosondes launched at Eureka then constrain sky-brightness temperature statistics. Those are verified with spectroscopic observations from the ground obtained with an Atmospheric Emitted Radiance Interferometer (AERI), a device essentially identical to one previously operated at Dome C, Antarctica (Walden et al. 2005). The model is described in Section 2. Afterword, in Section 3, archival spectra and contemporaneous sky-clarity estimates are presented from which emissivities and zenith sky brightnesses are extracted and global comparisons are made. Section 4 summarizes the results with some discussion of future prospects for all-sky polar infrared synoptic surveys from both hemispheres.

2. Model and Context

Within its transparent windows, thermal emission from the atmosphere approaches that of a blackbody. Below clear skies, radiant surface emission goes down proportionally with transmission: those photons not radiated to space. This was successfully applied in characterizing Antarctic plateau sites by assuming saturated air (e.g., Hidas et al. 2000), with the caveat that the inferred effective sky temperature is actually that of the peak in the thermal inversion. What is investigated in this study are the potential variations in atmospheric transmission and peak inversion temperature, which imposes limits on Arctic infrared sky brightness.

Consider downwelling radiation from a uniform horizontal slab of air at temperature, \( T \), and fixed emissivity, \( \epsilon \). Below it, the wavelength-dependent received flux, \( F \), commonly referred to in astronomy as a spectral “brightness,” is given by the Planck law, in units of Jy arcsec\(^{-2}\):

\[
F(\lambda, T) = 4.70 \times 10^{13} \frac{\epsilon hc}{\lambda^3} \left[ \exp \left( \frac{hc}{k_B \lambda T} \right) - 1 \right]^{-1},
\]

where \( h \) is the Planck constant, \( c \) is the speed of light in vacuum, and \( k_B \) is Boltzmann’s constant.

2.1. Transparency Range and Applicability

Only the thermal component of emission in \( K \)-band and redder is of interest here. Transparency of the atmosphere in this regime is primarily due to water vapor content; Eureka is extremely dry with a mean precipitable water vapor (PWV) in winter of 2 mm (Lesins 2010), with best conditions approaching 1 mm at PEARL (Steinbring et al. 2010). Zodiacal continuum emission makes a relatively small addition to the background near 2.3 \( \mu \)m, and a clean cutoff here avoids a plethora of narrow hydroxyl lines blueward. Moonlight is not important except at wavelengths shorter than 2 \( \mu \)m. For PEARL, moonless \( J \)-band (~1.2 \( \mu \)m) sky brightness is found to be similar to mid-latitude sites (Sivanandam et al. 2013).

Atmospheric emissivity longward of 2.3 \( \mu \)m is routinely simulated, with various codes available that can generate synthetic spectra. These sum the molecular absorption line by line, correcting for pressure and temperature within discrete atmospheric layers and outputting the resulting integrated transmission observable at the ground. This allows for experimentation with vertical atmospheric profiles and the molecular species modelled. Beyond water vapor and ozone, these might include methane, nitrous oxide, carbon monoxide, carbon dioxide, or other trace gases. In this study, a single parametrization with PWV was found to sufficiently capture variation in conditions within the passbands considered.

The ATRAN (Atmospheric TRANsmission; Lord 1992) library was employed, which was obtained from the Gemini website\(^1\), as used in their online integration-time calculators for infrared instruments. Figure 1 plots a range of transmission at zenith: the black curve is for 1.6 mm of PWV, the median for Maunakea.

\(^1\) http://www.gemini.edu/sciops/telescopes-and-sites
measurements to follow. Note that during this time, on only one occasion did a measured air temperature rise above 0 C.

One can see from the exponential dependence on $T$ in Equation (1) that for an atmosphere stratified into separate (and equally dense) layers of air it would be the layer with the warmest temperature which should dominate. However, those temperatures above the troposphere can safely be ignored for the infrared background discussed here. The hydroxyl emission associated with the upper stratosphere and mesosphere at $\sim1$ hPa has been explicitly excluded. Also, the relative pressures there are reduced by up to 3 orders of magnitude compared with the ground. For example, if temperatures were uniformly $-60$ C for pressures less than 500 hPa, this would constitute just about half of the atmosphere but contribute under 1% of the downwelling flux at 2.3 $\mu$m in Equation (1) if the remainder of the atmosphere were at 0 C. This fraction does grow as the surface temperature drops and toward longer emitting wavelengths, but the lower layer would still comprise over 63% of the emission at 20 $\mu$m if the surface temperature were instead $-40$ C.

Real vertical temperature profiles above Eureka in darkness are more complex, but can be effectively described as intermediate between that of a high-elevation, mid-latitude site and winter conditions for the South Pole. Seasonal behavior for the South Pole has been well characterized via Light Detection and Ranging (LIDAR) and high-altitude balloons by Pan & Gardner (2003); the thin black curve in Figure 2 indicates the average profile in July, which is during austral mid-winter. There is an acute inflection near the surface associated with the thermal inversion. Accordingly, a thick black curve shows the typical condition at Eureka in October through February for times when it is interior to the northern polar vortex, using spline fits to the profiles reported by Duck et al. (2000) in their Figure 5 (outside the vortex is indicated by a dashed curve). Duck et al. determined that Eureka fell inside or outside the vortex based on the 10-hPa pressure-level winds. Near-calm conditions characterize those times when Eureka is closest to being centered within the vortex, with the strongest winds corresponding to when it lies directly underneath. This has a significant impact on the upper atmosphere, but less so near the ground. Even during those times when Eureka is outside the vortex, the peak temperature of the surface-based inversion is raised, on average, by only a few degrees. However, this inversion condition does not always hold. When it is weak or nonexistent, surface temperatures may reach an extreme similar to that typical of a temperate site; a standard atmospheric profile with a lapse rate of $\gamma = -6.5$ C/km is shown for comparison. This has a scale height of 7.6 km yielding a constant ratio $(T_0 - T)/(\gamma \log(p_0/p))$, where $T_0 = 15$ C is the standard sea-level surface temperature, at pressure $p_0$ of 1014 hPa. As this exponential pressure profile seems generally applicable for heights above about $H = 3$ km to the tropopause —notice the parallel slopes with log-pressure of the grey points.
as well as the curve for the South Pole—a form with temperature falling as

\[ T = T_0 - \gamma H \]  

(2)

fits data in that regime, where \( T_0 \) refers to the local temperature at the surface assuming no inversion.

The usual winter condition for Eureka includes a strong thermal inversion, so it is instructive to look at the inter-season variation and for any longer-term trend in the inversion-peak temperatures that can occur. The monthly averages in Figure 3 show the peak temperature in the inversion over the entire set of aerosonde data available for Eureka. The average monthly temperature at the peak of the inversion is shown as a thin black curve. Those periods during dark months—October through February—are highlighted with a thicker black overlay; March and April are included as dashed curves. The same is shown for surface temperatures (dark gray). This helps illustrate that temperatures at the surface and at the peak of the inversion will, on average, drop throughout winter and not increase month-to-month again until well after sunrise; despite variation in surface temperatures over the past decades, the range of peak temperatures has been remarkably stable. The gray horizontal band is the mean peak temperature, plus and minus one standard deviation, \( \bar{T} \pm \sigma \). Other published atmospheric studies over this time period do not report specifi

2.3. Flux Correction for Thermal Inversion

The intent here is allow direct comparison of effective sky temperatures at Eureka with other sites, including mid-latitude mountains. Reforming the plots in Figure 2 via an exponential pressure profile, and normalizing to the surface elevation of the sites results in the curves shown in Figure 4. Note that, as anticipated, above 3 km from the surface (and below the tropopause) the standard atmospheric profile is suitable. This is shown as a thick dashed line for Eureka; a thin-dashed curve is for a surface temperature of 0 °C, appropriate for Maunakea. Similarly, the summit of Cerro Pachon would have a starting point of 9 °C (not shown). The light gray shading shows the range of temperatures obtained from all Eureka aerosonde profiles as described above: minimum through to mean values in 100 m altitude increments. Eureka surface temperatures can actually be colder than the peak of the inversion at the South Pole, which is usually 20 °C warmer in the first 300 m. The inversion at Eureka can also be of similar strength, but does not typically turn over until about 1 km up in the atmosphere.

The peak temperature is restricted, provided the standard temperature profile holds at higher altitude. Demanding \( H_{\text{peak}} = (T_0 - T_0')/(\gamma' - \gamma) \), where \( \gamma' \) refers to the lapse rate within the inversion, and \( T_0 \) is the surface air temperature, one can write

\[ T = T_0' - C'\gamma'H/\exp(H/H_{\text{peak}}). \]  

(3)

and if that meets smoothly with the standard atmosphere at twice \( H_{\text{peak}} \) (about 2 km to 3 km above the surface) the correction \( C' \) is given by \( e^{2 \cdot (1 + \gamma/\gamma')/2\gamma'} \). This is plotted as a thick gray curve in Figure 4 for \( \gamma' = 15 \) °C/km and \( T_0' = -40 \) °C, coinciding with the mean profile. Taking things one step further, for the case of \( \gamma' \approx (T_{\text{peak}} - T_0')/H_{\text{peak}} \), Equation (3) can be reduced to \( T_{\text{peak}} \approx T_0' + 3.74 \) °C when \( H_{\text{peak}} = 1 \) km. This is consistent with the near-vertical profile toward the warmer surface temperature in Figure 4. Therefore,
even when it is as warm as \(-25\) C in Eureka, the temperature at the peak of the inversion should still be less than \(-21\) C.

This simple relationship predicts a narrow distribution of thermal sky background above Eureka during periods when the inversion is present. Note that a difference in temperature up or down by 4 C would correspond to a scaling by just 20% in downwelling flux in Equation (1) at 5 \(\mu\)m, which suggests the following: the strength of the thermal inversion well constrains the downwelling flux, so for a given range of \(e\), the sky brightness below \(T_{\text{peak}}\) is readily recovered via \(F(\lambda, T_{\text{peak}})\); conversely, measuring the sky brightness and finding the peak temperature from the radiosonde should report a value of \(e\) for that wavelength. The fidelity of that model was tested with direct measurements of flux, as discussed in the following section.

3. Observations and Analysis

The Polar Atmospheric Emitted Radiance Interferometer (P-AERI) is a Fourier-transform moderate-resolution (1 cm\(^{-1}\)) infrared spectrometer that is sensitive in the 3.3 \(\mu\)m to 20 \(\mu\)m range. A two-channel detector utilizing photoconductive Mercury cadmium telluride (HgCdTe) coupled with photovoltaic indium antimonide (InSb) in a sandwich configuration is employed, housed in a dewar cooled to 70 K using a Stirling-cycle cooler. This spectrometer is illuminated through an infrared-transmitting window via a reflective optic in a housing outside in ambient air. By means of that tipping mirror, the sky spectra at zenith and calibration observations on either of two different blackbody sources (ambient and warm) are obtained. This instrument and its later version with an extended-range of sensitivity (E-AERI) are described in more detail in Mariani et al. (2012).

The P-AERI was operated by the University of Idaho from the Zero-altitude Polar PEARL Auxiliary Laboratory (OPAL), at 10 m elevation a.s.l., nearby the Eureka weather station. A near-continuous record with only a few short interruptions is available from full 2006 through spring 2009, during which it was employed to measure the absolute downwelling infrared spectral radiance for atmospheric physics studies. This and the E-AERI instruments were co-located during one year either side-by-side at this site or in concert from the PEARL facility roughly 15 km to the west of Eureka. The side-by-side data of several days were sufficient to allow verification of instrument specifications. The other observations were mostly in cloudy conditions, but sensitive enough to show the presence of very thin ice-crystal clouds, which affect surface radiative forcing (Mariani et al. 2012), although those data were not used directly here. Nonetheless, they are relevant to this analysis as the careful tests show excellent agreement between instrument calibrations, within 1% flux accuracy as expected in Knuteson et al. (2004). A small positive radiance bias of P-AERI has been noted and is being actively investigated; however, this would tend only to make those data slight overestimates of sky brightness (V.P. Walden, &D.D. Turner, 2016, private communication). This may also be relevant for possible direct intercomparison of future sky brightness measurements. For example, P-AERI has since been redeployed to Summit Greenland.

Those periods of clear skies in darkness are of most interest here, in particular at times when simultaneous atmospheric temperature profiles are available. To exclude any complication from daytime conditions, only those periods between October 21 and 20 February of each winter were considered, when P-AERI operated from OPAL. Processed spectra for those times were obtained from the the National Oceanic and Atmospheric Administration (NOAA) public archive. This includes 449427 individual spectra, or samples of roughly once per minute. These were obtained from the archive after 2015 September, when a fault in the high-frequency channel calibration was corrected and all data were reprocessed.

The median of all those spectra is shown in Figure 5. Model limits are also plotted: the light gray shows the result for convolving transparency at 1.6 mm of PWV with thermal emission at 0 C (Cerro Pachon, not shown, would be slightly higher); the thin black curve is Equation (1) for \(e = 0.05\) and \(T = -60\) C. Interestingly, it can be preferential at longer wavelengths to have a lower emissivity, even if temperatures are higher. The “ideal” case for Eureka of \(e = 0.005\) and

\[ C = \frac{3}{4} \]

\[ 11pp = \frac{2}{2} \]

\[ ftp://ftp1.esrl.noaa.gov/psd3/arctic/eureka \]
$T_{\text{peak}} = -30 \, \text{C}$ is shown as a thick dark gray curve; a dashed dark gray curve shows the “worst” case of $\epsilon = 0.20$. The light gray dashed curve is for values $\epsilon = 0.05$ and $T_{\text{peak}} = -22 \, \text{C}$.

### 3.1. Combined Data Set with Photometry

Basic meteorological observations are obtained hourly at Eureka, including pressure, surface air temperature, cloud cover, wind, and relative humidity. Relative humidity is essentially always near saturation in winter. Calm winds have been shown to correlate with good sky conditions at PEARL, but a more useful criterion here is the visual inspection of sky clarity from sea level. Although the observer’s assessment of sky clarity does not conform to a standard familiar in astronomy, usually expressed in eighths, best conditions do essentially correspond to what would be familiar as the best 1/8th elsewhere. A determination of “clear” by the meteorological observer denotes the complete absence of visible ice crystals in the atmosphere, which is known to correspond to truly photometric conditions at PEARL. The condition was reported in the hour immediately preceding 46,148 spectral records, or about 10% of the time. That is not to say that other times were not clear, but this visual confirmation verifies those cases when only atmospheric thermal emission was likely to be important.

For each P-AERI spectrum, photometry was performed in the most transparent portions of $L_p$, $M_p$, $N_a$, $N_b$, and $Q$ band averaged over a 0.2 $\mu$m bandpass centered at the wavelength specified in Table 1. The winter of 2008/2009 illustrates the available data as shown in Figure 6. The other two seasons are similar. A filled circle in the top panel indicates those times when skies were visually confirmed to be clear. The top panel plots the height of the inversion peak, as measured from the radiosonde data. A spline was fit to the data to retrieve this; these data points are those for which there is at least one associated P-AERI spectrum, that is, taken within 30 minutes of the launch. This includes some 15645 spectra, or about 3.5% of the total sample. The middle panel gives the surface temperature from the Eureka weather station records (dark gray points) and the peak temperature obtained from the radiosonde launches (dark circles). The light gray horizontal dashed lines indicate the mean value of $T_{\text{peak}} = -22 \, \text{C}$ and $H_{\text{peak}} = 1.0 \, \text{km}$.

### 3.2. Identifying Clear Sky Conditions

Photometric conditions in the optical from PEARL correspond directly with the lack of ice crystals in the lower atmosphere, which are known to occur about 50% of the time (Steinbring et al. 2012). Therefore, visual confirmation of clear skies from sea level coincident with a radiosonde provides a check on the correctness of the simple model prescription of thermal sky brightness for PEARL. Figure 7 gives the distributions of associated inversion peak height, temperature and the lapse rate for every profile obtained. The dark outlines are for confirmed clear sky conditions only; the gray shading is for other times. Importantly, under clear skies there is a well-defined range of inversion peak height, confined within 0.5 km to 1.5 km. See also the narrow distributions of peak temperatures at all times and how the lapse rate distribution is notably different for clear skies than otherwise. This confirms that clear skies are associated with a strong inversion and that

### Table 1

| Bandpass | $\lambda$ ($\mu$m) | $F_{\text{median}}$ | $f$ | $\ell$ |
|----------|-------------------|---------------------|-----|-------|
| Kd       | 2.4               | $1.7 \times 10^{-4}$ | 3.1 $\times 10^{-4}$ | 0.050 |
| Lp       | 3.8               | $3.6 \times 10^{-2}$ | 1.3 $\times 10^{-1}$ | 0.023 |
| Mp       | 4.7               | 1.2                 | 2.0 | 0.039 |
| Na       | 8.3               | 31                  | 64  | 0.038 |
| Nb       | 11.0              | 32                  | 130 | 0.034 |
| Q        | 18.8              | 460                 | 550 | 0.078 |

**Notes.**

- In units of Jy arcsec$^{-2}$.
- Results based on the model in this paper.
the breakdown of the inversion is more likely to be associated with cloud.

3.3. Extraction of Emissivity

The coincidence of radiosonde profiles and P-AERI brightness measurements from sea level allows a straightforward measure of emissivity across all of the bands in question. This follows from inverting Equation (1), and directly reporting emissivity for the observed $T_{\text{peak}}$; results are plotted in Figure 8. The light gray shaded regions are all data and the dark outlines indicate those observations obtained when it was known to be clear in Eureka. Note how similar these results are to the expectations from the atmospheric transmission model of Section 2, particularly under clear skies; typically a range of emissivities consistent with $\epsilon = 0.005$ to 0.05. The cause of the secondary “bump” toward higher emissivity at 18.8 $\mu$m is unknown, but was evidently not associated with photometric conditions. A hard upper limit of $\epsilon = 0.20$ is also consistent with that used by Hidas et al. (2000) in characterizing South Pole infrared backgrounds.

Although instrumental error on individual fluxes per band is near 1%, uncertainties in recovering the instantaneous peak inversion temperature, and thereby an estimate of emissivity, are necessarily larger. This is less easy to characterize per sample because it must involve error in both the temperature and pressure measurements (0.5 C and 25 Pa at each elevation) along with the fidelity of their profile fits. That is not precisely the same as the true effective sky temperature, and does not account for temporal fluctuation during a balloon flight. Systematic error in predicting the sky brightness at PEARL can still be constrained though. Over the ensemble, this is conservatively well within the 4 C peak inversion temperature standard deviation, which scales flux to within 20%, declining to 5% as the observing wavelength tends to 20 $\mu$m. Knowledge of true effective sky temperature is plausibly within 2 C, similar to the difference in surface temperature at 600 m and warmest inversion peak; a global 10% uncertainty in emissivity is a reasonable guide, as well as to characterize the real sky brightness distribution, which follows.

3.4. Brightness Distributions and Comparison

Distributions of observed brightness in bands $L_p$, $M_p$, $N_a$, $N_b$, and $Q$ were calculated. Results are plotted in Figure 9. For comparison, the gray curves outline the simple model of
high values of emissivity (those rarer times associated with thick cloud) are those times associated with higher sky brightness.

The simple model also helps compare thermal background between different sites under photometric skies: at one limit is an idealized sky brightness, taken to be Equation (1) with the “ideal” emissivity of $\epsilon = 0.005$ and $T_{\text{peak}} = -30$ C; shown as a thick vertical gray line in Figure 9. Note how this emphasizes the sharp dark edge of the $L_p$ sky emission. This is expected, as it is near the wavelength at which this “ideal” case overlaps that of mean transparency, but coldest conditions (see Figure 5). In other words, this is where the advantage of colder conditions can begin to overcome poorer transparency, which also explains how the extreme temperatures of the South Pole (down to $-60$ C) can result in lower emission, even when $\epsilon = 0.05$. The median and mean sky brightnesses in each observed band are tallied in Table 1. Not surprisingly, there is less difference between Arctic and Antarctic at long wavelengths, but improvement over a high mid-latitude site at short wavelengths becomes significant. For example, using $\epsilon = 0.05$, the mean model value for Cerro Pachon at $L_p$ is 2 Jy arcsec$^{-2}$; Maunakea is 1 Jy arcsec$^{-2}$, rising to 6 Jy arcsec$^{-2}$ at $M_p$. In the $N$ window, near 8.9 $\mu$m, Chamberlain et al. (2000) report that the South Pole has a nighttime median of 50 Jy arcsec$^{-2}$, which is about the same as found at Eureka with P-AERI. Although the data are for austral summer temperatures, estimates at Dome C do not improve greatly on this at longer wavelengths: there, $N_b$ reaches 43 Jy arcsec$^{-2}$ and 310 Jy arcsec$^{-2}$ at $Q$ (Walden et al. 2005), which are not quite a factor of two better.

Finally, a confident extrapolation shortward into $K$ band can be made. A conservative upper bound on sky brightness is obtained from assuming a “worst” case of $\epsilon = 0.20$ and $T_{\text{peak}} = -18$ C, shown as a thick dashed gray vertical line in Figure 9 in the panel depicting $K_b$. Together with the measured distribution of inversion temperatures, this bounds the full range of thermal sky brightness in the $K_b$ band; clear skies are almost never brighter than 850 $\mu$Jy arcsec$^{-2}$, with a median of 170 $\mu$Jy arcsec$^{-2}$ (the vertical light gray line) for $\epsilon = 0.05$. This is a dramatic improvement over temperate sites. For comparison, at 2.4 $\mu$m, the thermal sky background is then about 4 mJy arcsec$^{-2}$ at Gemini North, and 8 mJy arcsec$^{-2}$ for Gemini South. Here, PEARL would be a order of magnitude darker on average, and possibly as much as a factor of 40. In fact, this is comparable to the measured median and third-quartile values at the South Pole between 155 and 270 $\mu$Jy arcsec$^{-2}$, although not quite as low as the best quartile of 80 $\mu$Jy arcsec$^{-2}$ quoted by Lawrence et al. (2002).

4. Summary and Conclusions

Archival measurements of the thermal infrared downwelling flux above Eureka on Ellesmere Island, Canada, have been
presented. Three complete winter seasons sampled typical variation in thermal inversion temperature. Available meteorological data have been compared with other atmospheric studies which verify that reliably cold, clear conditions for the PEARL site at 600 m elevation will result in dark skies in the infrared during winter, the first time this has been shown for a High-Arctic mountain site. Contemporaneous visual estimates of sky clarity with twice-daily balloon-borne radiosonde profiles of air temperature allow extraction of the atmospheric transmission in $L_p$, $M_p$, $N_a$, $N_b$, and $Q$ bands.

A simple model of thermal emission provides a good general fit to these data and allows extrapolation into $K$ band. Skies at 2.4 $\mu$m should be particularly dark, more than an order of magnitude better than for current mid-latitude infrared observatories; Gemini North and South are used for comparison here as they analogously allow access to both hemispheres. Darkness is comparable to the South Pole under clear skies. Unfortunately, 2.4 $\mu$m is shortward of P-AERI sensitivity, which was sampled at zenith only. Direct confirmation in $K_d$ with a dedicated instrument would be desirable, especially characterization of airmass dependence. This will be influenced by the aerosol content of the lower atmosphere, in particular the vertical distribution of diamond dust, which differs from the Antarctic plateau.

Beyond the important primary result of dark skies in the thermal infrared, knowledge of the other observing conditions for PEARL permits a secondary inference to be drawn. The rooftop observing platform of PEARL can provide excellent seeing under calm, clear conditions, with a median under 0$''$.76 in $V$ at 8 m elevation (Steinbring et al. 2013). Relative to the South Pole, this constitutes a significant improvement, as it is well known that optical seeing within its strong inversion layer is poor: 1$''$.9 ± 0$''$.6 average and standard deviation in $V$ at 7.5 m elevation (Travouillon et al. 2003). For a given point source with the same sky brightness, this is typically a gain of $S/N \approx 2.5$ for PEARL due to allowing a smaller, optimized photometric aperture, or effectively a gain of a magnitude in depth for the same exposure time. In AB magnitudes 200 $\mu$Jy arcsec$^{-2}$ corresponds to 18.1 mag arcsec$^{-2}$, less than a magnitude brighter than best conditions at the South Pole; the implication is that the disadvantage of warmer conditions at PEARL relative to South Pole is counterbalanced by better photometry. The combination of the two sites could be very powerful in the era of long-term time-domain surveys, as it

![Figure 8. Histograms of inferred emissivity at given wavelengths in the five bands under study (gray shading). Results for those times which were known to be clear simultaneously with a radiosonde profile are indicated by the dark outline. Measured mode, median, and means are indicated by vertical solid, dashed, and dot-dashed lines, respectively.](image-url)
exploits their offset observing seasons and particularly dark skies in $K$ - together providing greatly improved efficiency over temperate sites. One program is already anticipating a survey employing twin $K_d$-optimized telescopes for South Pole and PEARL to take advantage of this “bi-polar” astronomical opportunity (Moore et al. 2016).

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