What to do when the sky is blue
notes from practice on the use of colored sky models

Michael Beggs, Loisos + Ubbelohde
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This talk presents some of our observations on the use of colored sky models for radiance in the context of our work as a consulting practice that works in a variety of locations, project scales, and levels of analytical complexity.

It is divided into five sections, roughly

Introduction (we’re in the middle of this right now)

The Sky

The Model

Post Processing

The future
Point-in-time view-based simulations are central to our consulting process. These images are instantly accessible and contain a wealth of data, but the process to produce them accurately requires extensive coordination with designers as well as time-consuming preparation of the simulation model to ensure exactness. This means that we need our radiance results to be both highly accurate and beautiful.
Introduction: Perceiving the Color of the Sky

Sir James Jeans' metaphor for atmospheric scattering from “Why the Sky is Blue”, 1931
Introduction: Perceiving the Color of the Sky

Sir James Jeans’ metaphor for atmospheric scattering from “Why the Sky is Blue”, 1931

It is worth reminding ourselves that color is a perceptual phenomenon.

What we call the visible spectrum is the range of wavelengths for which humans have the visual response that we call color.

Radiation, reflection and transmission exist physically in the world, but color as we experience it exists only within the human mind and body.
Introduction: Perceiving the Color of the Sky

As such we cannot perceive color as illuminance, we can only perceive it when it is reflected or scattered by something.

In architecture, that more or less happens in three places:
Introduction: Perceiving the Color of the Sky

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Reflected on (interior) building surfaces
Introduction: Perceiving the Color of the Sky

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Reflected on (interior) building surfaces

Reflected or scattered from the outside
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In architecture, that more or less happens in three places:

1. Reflected on (interior) building surfaces
2. Reflected or scattered from the outside
3. Scattered within transmissive materials
Introduction: Perceiving the Color of the Sky

The color of the daylight seen by building interiors varies both by orientation...

Two measurements of the color of daylight taken in the same location at the same time, one pointed directly at the sun, the other at the dark blue sky opposite of the sun, show the greatly varying spectra of daylight.
Introduction: Perceiving the Color of the Sky

The color of the daylight seen by building interiors varies both by orientation...

... and by weather condition and time of day

Two measurements of the color of daylight taken in the same location at the same time, one pointed directly at the sun, the other at the dark blue sky opposite the sun, show the greatly varying spectra of daylight.
The Sky
The Sky

The sky models
Which sky models we prefer
When we use them
Special considerations when using the Utah sky model
The Sky : The Sky Models

July 28th, 14:00 - clear sky
Los Angeles, CA (34° N. Latitude)

pcond human adaptation renderings

Standard Gendaylit Sky
(gendaylit 7 28 13.5 -W 769.0 196.0 -a 34.02 -o 118.45 -m 120 )

Gendaylit Colored Sky
(gendaylit + colorfunc skyfunc)

Standard Utah Sky
(gendaylit + colorfunc skyfunc
as described in utah.cal)

L+U Modified Utah Sky
(Utah Sky color model with Perez-based luminance distribution)

We modify the values of skyfunc to give a slight blue cast
to the sky when using gendaylit for clear conditions.
The Sky: The Sky Models

July 28th, 13:00 - clear sky
Los Angeles, CA (34° N. Latitude)

falsecolor luminance maps

Standard Gendaylit Sky  
Gendaylit Colored Sky  
Standard Utah Sky  
L+U Modified Utah Sky  

cd/m²
60,000 30,000 15,000 7,500 3,750 1,875 937.5 468 234 120 60
The Sky: The Sky Models

July 28th, 14:00 - clear sky (Los Angeles, 34ºN)


Window faces south
The Sky: The Sky Models

- Standard Gendaylit Sky
- Gendaylit Colored Sky
- Standard Utah Sky
- L+U Modified Utah Sky

July 28th, 14:00
- W 769.0 196.0

February 5, 11:00
- W 681.0 180.0

May 24th, 18:00
- W 290.0 141.0
At the moment, the colored gendaylit model is not suitable for most of our applications because:

- Lack of support for mixed or intermediate skies limits sky conditions for which the model is practical
- The sky model is too blue, particularly at the horizon, for the latitudes at which we generally work.
February 5, 11:00

The Sky: The Utah Sky - Luminance and Illuminance

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The Sky : L+U’s Modified Utah Sky

L+U Modified Utah Sky

Some notes on L+U use of the Utah Sky Model

- We use a modified version of the Utah sky model that combines the Utah color model with a peretz distribution for luminance and illuminance.

- We do not use the Utah sky for overcast conditions. Typically, we will use the Utah sky only for clear conditions (when direct irradiance is more than 2x indirect).

- Otherwise we use gendaylit.
Some notes on L+U use of the Utah Sky Model

- For clear sky conditions we tend to set the turbidity to 0 as we have found that more turbidity tends to result in overly warm afternoon skies, which can look dirty at the horizon.
L+U Modified Utah Sky

Some notes on L+U use of the Utah Sky Model:
- The exception to this rule is in the late afternoon if we need to create a dusk or sunset image.

May 24, 18:00
_turbidity_0

May 24, 18:00
_turbidity_5

May 24, 18:00
_turbidity_20
High-turbidity dusk Utah Sky used in electric lighting integration simulation when sky will have little to no interior contribution.
Sometimes we will transition from a non-color gendaylit sky to a Utah sky as the project develops and as simulation models become more complex.
The Model
The Model
Color and orientation
Detail and color
Use of site models
The Model: Color and Orientation

Simulation models that are largely greyscale, particularly greyscale models with one orientation, will be susceptible to the influence of exposure to the blue sky.

Generally both of the images shown above are too blue to match human experience. This level of interior blueness will be distracting to the client and disrupt conversation and comprehension.

There is a dissonance between the level of abstraction of the greyscale model and the specificity of the colored sky model.
Choosing a time when sun enters the space helps to balance the daylight spectrum within the room, but showing direct sun entry can lead to other potential distractions in conversation with a client.

The addition of a second orientation helps here, but since the clerestory faces north, and the building roof is grey, the overall effect is still very blue.
The Model: Color and Orientation

Jun 21 12:00 - Clear Sky

December 12 12:00 - Clear Sky

North
The Model: Color and Orientation

Jun 21 12:00 - Clear Sky

December 12 12:00 - Clear Sky

Jun 21 12:00 - Clear Sky

December 12 12:00 - Clear Sky

North

North
The Model: Color and Orientation

Jun 21 12:00 - Clear Sky (9,800 fc)

December 12 12:00 - Clear Sky (5,200 fc)

February 24 12:00 - Overcast Sky (3,500 fc)

View from door to East

View to West

fc
200
180
160
140
120
100
80
60
40
20

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The Model: Detail and Color

Simple, mostly greyscale model, window faces south

Mostly greyscale model, window wall faces north
Adding color and detail to the simulation model helps to either disguise the blue cast from the sky model or to balance the visual field so that this cast is less noticeable.
One potential problem with making the model colored or textured is the potential problem of warm colored materials being located within models that are mostly or entirely north-facing.

In the case of the images here, the overcast sky simulation appears warmer than the clear sky simulation. This is partly a problem of direct comparison and also a problem of white balance, which we will return to later.
Overcast February sky (gendaylit).

The comparison is slightly improved by using a lower sun angle, where more directional direct sun strikes the ceiling fins.

(The trans material used for the skylight glazing has a minute amount of specular transmission to match the specified diffusing interlayer for the skylights.)

Clear September sky (L+U modified Utah sky)
Adding a site model, particularly a site model that includes colored elements, will both make the blue cast more believable and also add additional colors to the ambient light spectrum.
One unexpected consequence of adding a site model was this project for a set of offices located in a renovated pier building.

We used the basin method, as described on the radiance discourse site, for building the water around the pier (surface of the water is dielectric with a functional texture added through wrinkle.cal, with an opaque bottom and sides beneath.

This had the unintended consequence of reflecting the blue of the sky model up onto the ceiling of the offices giving them a very blue cast. The water also appeared very blue, which turned cyan once the image was conditioned.
We controlled the appearance of the water by a combination of masking the exterior view and selectively blending in a greyscale (luminance only) version of the same area and carefully white balancing the interior portion of the image.

Overcast December sky (gendaylit). View is oriented to southwest.

Clear June sky (L+U modified Utah sky) - white balanced and made partially greyscale.
Post Processing
Post Processing

Pcond and colored skies
White balancing
White balance in electric lighting integration
Post Processing : Eek!
Post Processing : Eek!

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Post Processing: Eek!

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Post Processing: Eek!

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Post Processing: Eek!
Yikes! What happened here?
Understanding Radiance RGBE and Pcond

This is a smart way of handling colors because it allows a very broad range of possible illuminance or luminance values (76 orders of magnitude), albeit without enhanced color fidelity (you still only have 8-bit color).

However, it poses problems when it comes time to tone or condition images.

\[
\text{illuminance} = 179 \times (0.265R + 0.67G + 0.065B) \\
\text{illuminance} = 179 \times (0.265\times0.92 + 0.67\times1 + 0.065b\times0.4) \\
\text{illuminance} = 168.26 \text{ lux}
\]
To output a standard dynamic range image, we need to map all these disparate 0-1<sup>exp</sup> pixels to the same 0-1<sup>1</sup> scale for display.

`pcond -h` does this using a mapping that mimics the responses of the human visual system.

BUT, in order to use it most effectively, you need to tell it what bounds it is mapping to.

`Pcond` does this to give us some flexibility about what our simulation channels might mean and to enable the process of adaptation to adapt to the capabilities of different output devices.
This means that we need to give Pcond a sense of the bounds of red, green, and blue that our output device supports.

In the digital imaging world, these are called colorspace.

We primarily produce PDF reports, which inherently use JPEG compression. This means more or less everything we make will get packaged in the sRGB color space, regardless of the output device on which our presentations will be viewed.

This means using these coordinates for RGB:

\[
\begin{align*}
x_r &= 0.64 \\
y_r &= 0.33 \\
x_g &= 0.30 \\
y_g &= 0.60 \\
x_b &= 0.15 \\
y_b &= 0.06 \\
x_w &= 0.3127 \\
y_w &= 0.348
\end{align*}
\]
Understanding Radiance RGBE and Pcond

Pcond does not assume a colorspace by default. We can set it using the -p flag.

-t stops preceded by a `+` or `-`. This option implies a linear response (see the -l option above).

-u Lmax Specifies the top of the luminance range for the target output device. That is, the luminance (in candelas/m²) for an output pixel value of (R,G,B)=(1,1,1). The default value is 100 cd/m².

-d Ldmin Specifies the dynamic range for the target output device, which is the ratio of the maximum and minimum usable display luminances. The default value is 32.

-P xk yk zk xb yb zb xw yw Specifies the RGB primaries for the target output device. These are the 1931 CIE (x,y) chromaticity values for red, green, blue and white, respectively.

-f macbeth.cal Use the given output file from Macbethcal(1) to precorrect the color and contrast for the target output device. This does a more thorough job than a simple primary correction using the -p option. Only one of -f or -p may be given.

-x mapfile Put out the final mapping from world luminance to display luminance.

So we could run pcond -h -p .64 .33 .30 .60 .06 .3127 .348 to get a human-adapted image conditioned to the sRGB colorspace.

If we want to preserve the equal-energy white point of the Sharp RGBE color model, we can modify the xw and yw coordinates to 0.333 and 0.333 without significantly changing the appearance of the image.

This is a shift from the D65 illuminant to the E illuminant. And is extremely subtle. Can you tell the difference between the images below?
Post Processing: Pcond with sRGB Primaries

`pcond -h -v - without primaries specified`

`pcond -h -v - with sRGB primaries specified, modified to use E illuminant
  x_r .64  y_r .33  x_g .30  y_g .60  x_b .15  y_b .06  x_w .333  y_w .333
  (pcond -h -v -p .64 .33 .30 .60 .15 .06 .333 .333)`
Post Processing: Pcond with sRGB Primaries

- pcond -h -v: no colorspace specified
- pcond -h -v: with sRGB + E colorspace
A final, related aspect is considering the relationship between the conditioned image and what we would expect the space to look like from experience. We will sometimes use custom gaussian distribution inputs to pcond to modify the exposure and conditioning of the image.

We also use this method to give exactly the same exposure to different sky conditions, to show difference (remove the variable of local adaptation).

This can also be accomplished, though without the advantages of the gaussian distribution, using the exposure flag in pcond.
Post-Processing: white balancing

We use pfilt to colorshift images along the black-body curve without changing the absolute luminance of the output image. This gives us control over the white point of the image, so that we can consider local color adaptation alongside adaptation to luminance.
Post-Processing: white balancing

- No shift, standard pcond
- 5000k > 4000k, standard pcond
- 5000k > 3500k, standard pcond

- No shift, sRGB + E pcond
- 5000k > 4000k, sRGB + E pcond
- 5000k > 3500k, sRGB + E pcond
White balance is also an important consideration in electric lighting integration simulations, where we want to show that the light sources are of different color temperatures, while keeping in mind that an occupant of the room will rapidly adapt to both color temperatures without noticing it.

- **Equal-energy - no white balancing applied**
  (5000k daylight + 5000k electric lighting)

- **Warm electric lighting, neutral daylighting**
  (5000k daylight + 3000k electric lighting)

- **Warm electric lighting, cold daylighting**
  (6000k daylight + 3000k electric lighting)
In this room, which faces directly east, the bluish cast of an uncorrected midday-afternoon sky is understandable in a daylight-only simulation, but looks green and harsh when the warmer electric lighting is added. The multiple colors of light are particularly noticable and distracting on the all-grey furniture.

The effect is somewhat reduced by the use of appropriate colorspace primaries, but this remains a difficult scene to understand.
By comparison, the scene is more coherent with a greyscale gendaylit overcast sky.
In other cases, the addition of electric lighting, even of strongly different color temperature, makes the blue cast of daylight look more natural. Here the simulation produces an image that is consistent with our experiences of daylight within electrically-lit spaces.
The Future

Cyanometer by Horace Bénédict de Saussure, 1789
The Future
Localized color
Fine control of daylight color
Into the unknown

Cyanometer by Horace Bénédict de Saussure, 1789
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19th Annual Radiance Conference, August 19-20th 2021

Cyanometer by Horace Bénédict de Saussure, 1789

Blue in the 39th degree measured on Mont Blanc by de Saussure in 1786

Blue in the 46th degree measured on Chimborazo by Alexander von Humboldt in 1802
We are considering ways to more accurately describe the subtle differences in the colors of daylight between locations and climates. This involves creating methods in which there is a useful feedback between simulation sky models and measured or monitored data.
The Future: Localized Color

December clear sky with north-facing diffusing sawtooths

December clear sky with louvered horizontal diffusing skylights
The Future: fine control

Colored sky model + Optics glazing definitions = Model with glazing specific color reflectance and transmittance
We are aware of the work Solemma has done building upon radiance to create Alfa to simulate circadian-related lighting conditions, amongst other uses. We have not done this kind of simulation because we have not had clients ask for it. For 99% of architectural daylighting services, 3 channel RGB is more than enough information, and presents more than enough potential gaps and pitfalls in creating accurate simulations.
Openness: 3%
Color: 1519 Silver Birch
VLT (measured): 8.8%
VLT (per manufacturer): 8%
Transmitted Color Temperature*

* with 5000K direct sun source

Notes
Pros:
Low contrast within shadecloth
Medium screening of bright objects / sun
High VLT

Cons:
Moderate warm color shift

Skylight Appearance

Direct Sun / Glare

Color Transmission

Normalized Spectral Distribution

Spectral Transmission

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19th Annual Radiance Conference, August 19-20th 2021
The Future: into the unknown

View of San Francisco, Midday, September 9, 2020

Berkeley, California, September 9, 2020, 12:16pm
Climate change will reshape local climates in ways that will take us completely by surprise. We may not find ourselves simulating wildfire skies anytime soon, but we are, even anecdotally, already seeing increasing variability in sky conditions.

In this context, maintaining flexibility, and developing simple methods for calibrating simulation skies to measured or monitored data, may become essential parts of good daylighting practice.

And for some projects, that will also mean understanding the color of the sky.