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Technical Groups

Sky Optics: Colors and Spectra of Clear Daytime and Twilight Skies

Featuring Raymond L. Lee, Jr.
13 January 2022

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About the Color Technical Group

Our technical group focuses on all aspects related to the physics, physiology, and psychology of color in biological and machine vision.

Our mission is to connect the 900+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- Special webinar on display calibration
- Vision science in times of social distancing bi-weekly coffee breaks
- Incubator meetings

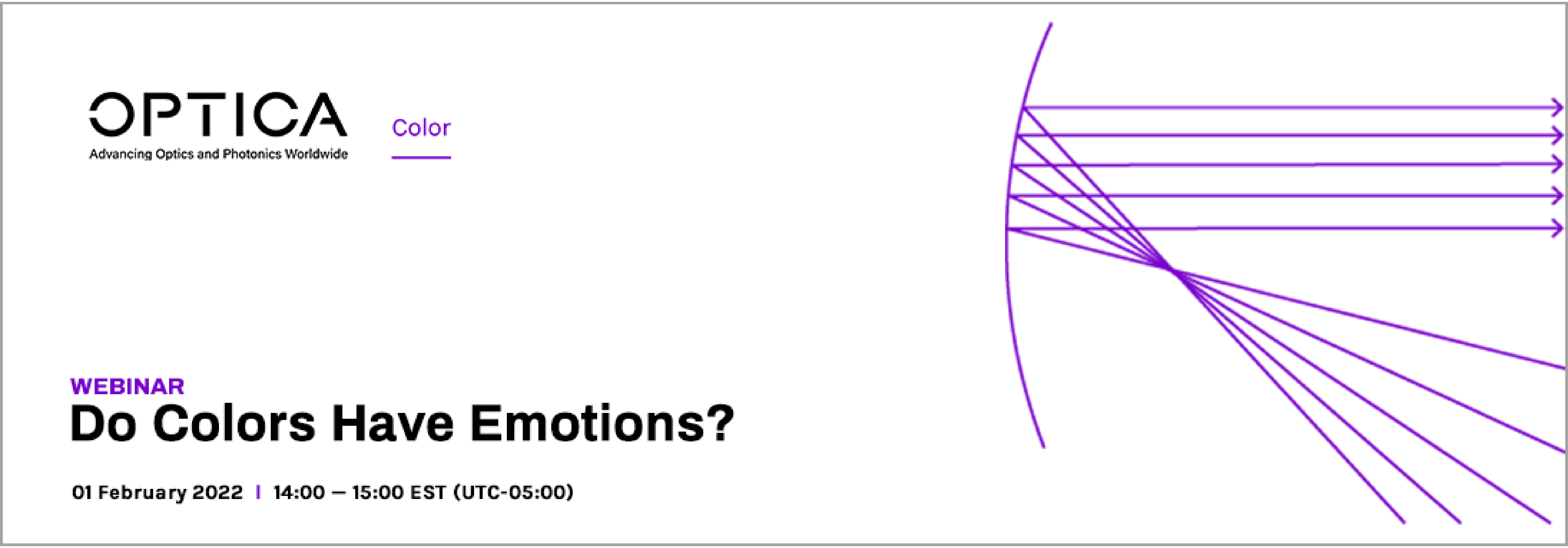
Connect with the Color Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

- Our website at www.optica.org/VC
- On Twitter at #OSAColorTG
- On LinkedIn at www.linkedin.com/groups/13573604
- Email us at TGactivities@optica.org

Upcoming Webinars



Upcoming Webinars

OPTICA
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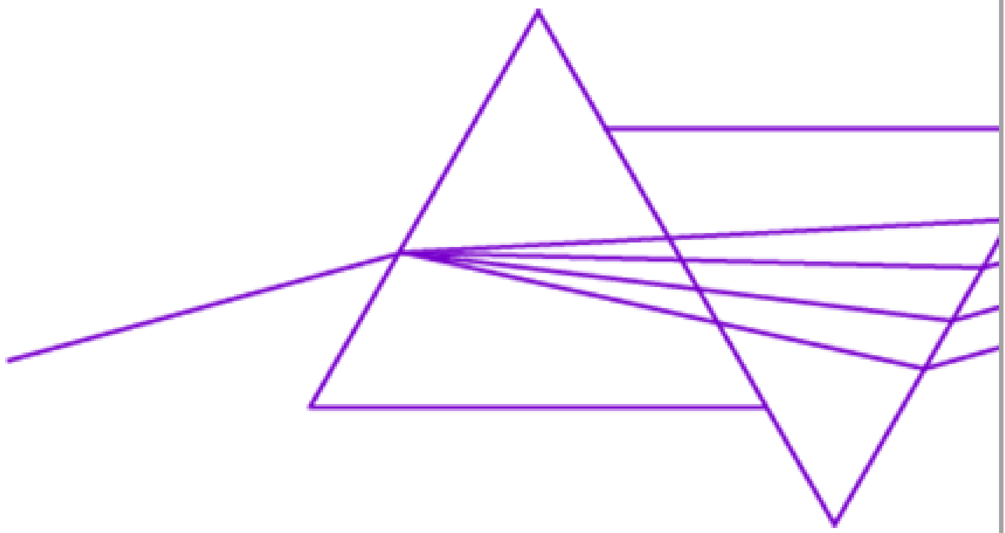
Color

WEBINAR

Measuring Light, Color, Spectrum and Personalized Light Exposure Using Wearable Light Sensors



11 February 2022 | 11:00 — 12:30 EST (UTC-05:00)

Raymond L. Lee, Jr.

Until 2021, Raymond L. Lee, Jr. was a Research Professor at the U. S. Naval Academy in Annapolis, Maryland, where he also taught midshipmen in the departments of Mathematics, Oceanography, and Physics. Lee's scientific research in atmospheric optics and radiative transfer has been supported by a series of National Science Foundation grants, from which he has published 28 peer-reviewed technical papers in OSA journals and a scholarly book on the natural rainbow's scientific and cultural history (The Rainbow Bridge: Rainbows in Art, Myth, and Science; Penn State Press; 2001). Lee has been an Optical Society member since 1996 and an American Meteorological Society member since 1978.

Sky optics: Colors & spectra of clear daytime & twilight skies

Raymond L. Lee, Jr.
Research Professor (emeritus)
United States Naval Academy
Annapolis, Maryland

Support: U. S. National Science Foundation grants
AGS–0914535 & AGS–1664404

Q: So why *is* the sky blue?

A: Molecules are much smaller than wavelengths λ of visible light.

Succinct but not very satisfying, so use 2 different paths to reach the same answer.

(1) From William Strutt's (later Lord Rayleigh) 1871 **dimensional analysis**:

(a) scattering by a small spherical particle of radius $R_p < \lambda/10$ is $\propto$ its volume V ($= 4/3\ \pi R_p^3$) because the particle's constituent atoms will scatter in phase,

(b) scattered light's amplitude E_s is $\propto V$ & to E_i, the incident light's amplitude,

(c) energy conservation requires scattered irradiance E_s^2 to decrease with distance r as $1/r^2$ & so scattered amplitudes decrease as $1/r$,

(d) meaning that $(E_s/E_i)^2 \propto V^2/r^2$, and for dimensional balance the

(e) ratio must include a 1/length^4 factor, with $1/\lambda^4$ being a plausible choice.

(2) Strutt's more rigorous explanation is, in modern form:

(a) for light speed c, angular frequency $\omega = 2\pi c/\lambda$, time t, phase angle δ, & max amplitude E_0, the time dependence of E_i is $E_i = E_0 \sin(\omega t - \delta)$, so that

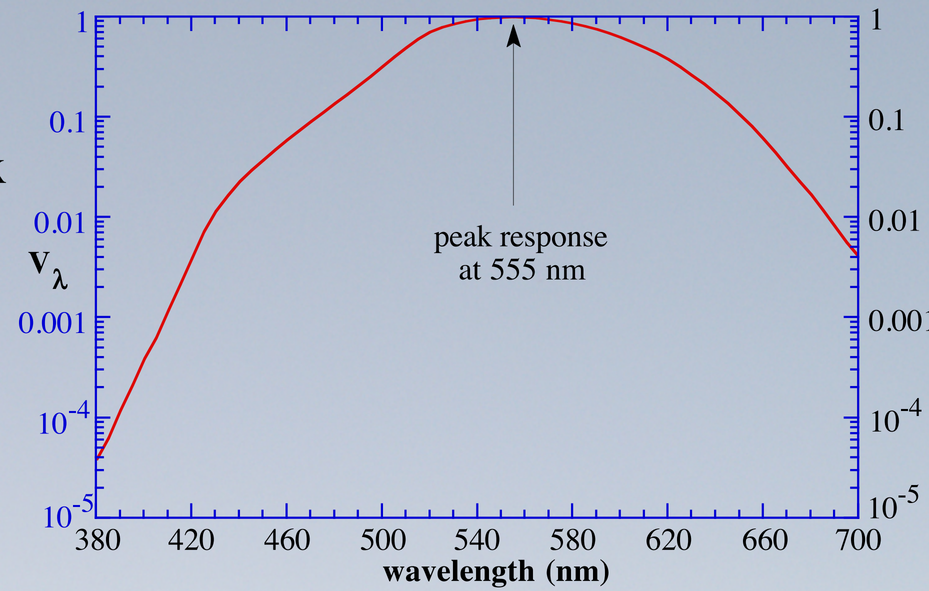
(b) **acceleration of scattered waves** $E_s \propto \partial^2 E_i/\partial t^2 = -\omega^2 E_i = -(2\pi c/\lambda)^2 E_i$,

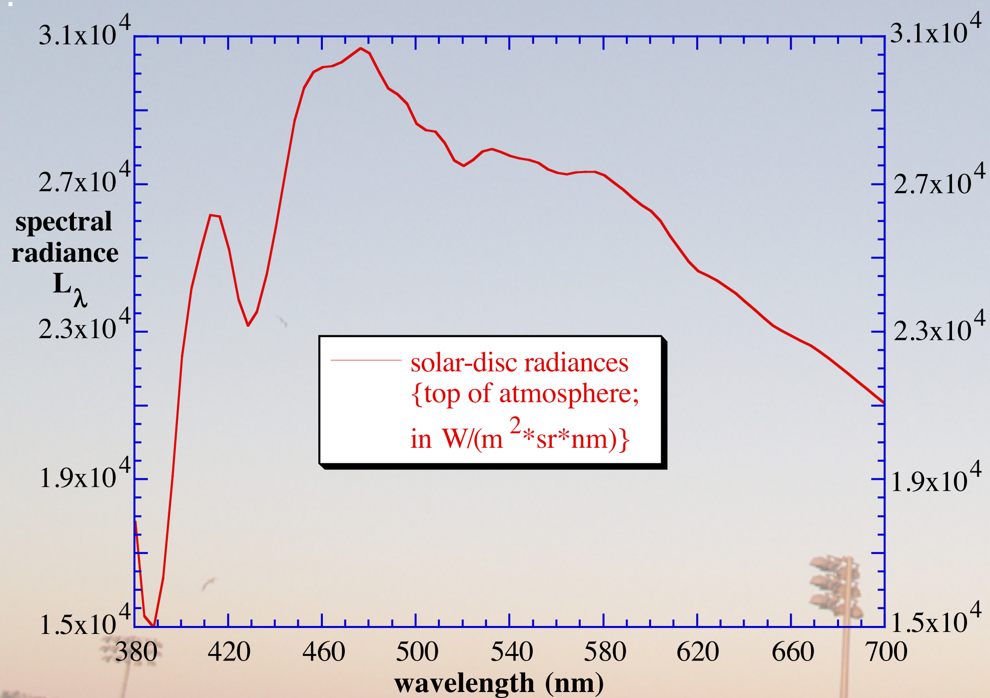
(c) or $(E_s/E_i)^2 \propto 1/\lambda^4$, & so scattered skylight has a pronounced blue bias.

Q: Then why isn't the clear sky always the *same* color everywhere? And why isn't that color violet, not blue, if scattering is $\propto 1/\lambda^4$?

A: Perception and physics.

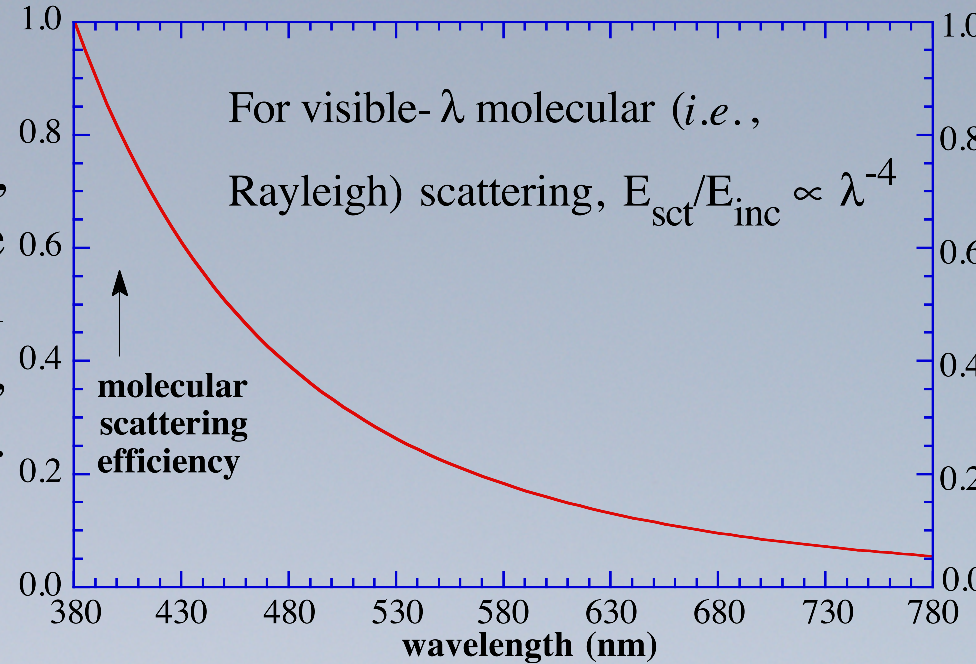
(1) Photopic sensitivity V_λ is ~ 3500 x greater at 480 nm than at 380 nm.

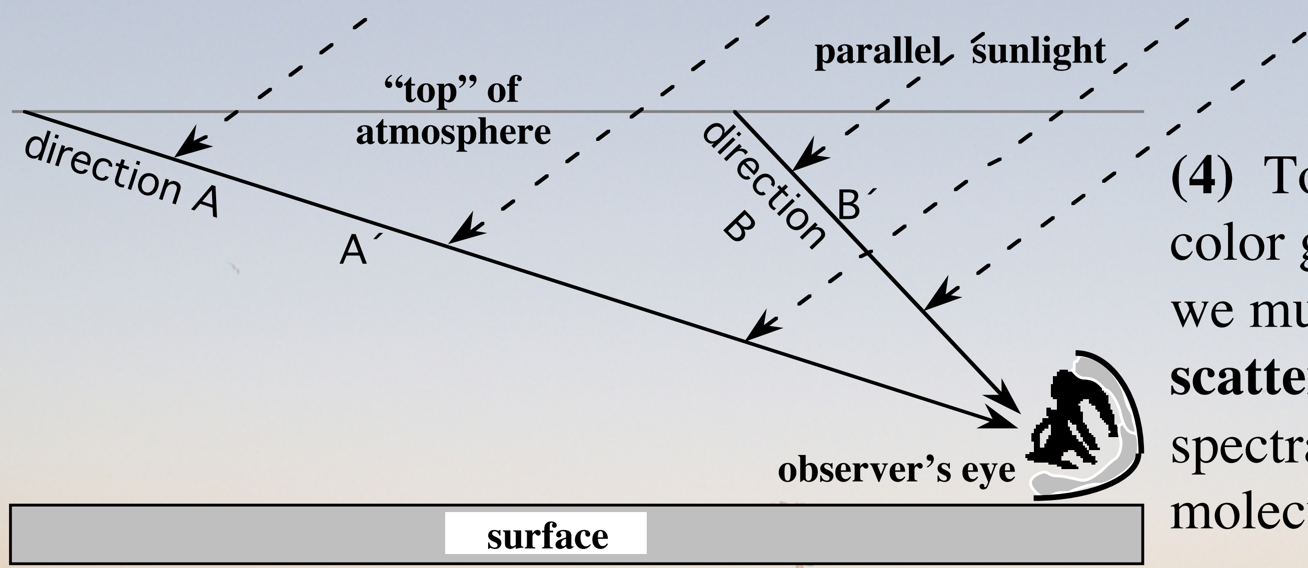




(2) Skylight's source in extraterrestrial sunlight has much less energy at violet λ.

(3) Skylight isn't light of a *single* λ, but a continuum of many λ that are spectrally integrated by the visual system into 3 broad-bandwidth signals, thus obscuring spectral extremes.





(4) To explain the clear sky's color gradients & white horizon, we must consider how **multiple scattering** transforms the spectrally consistent λ^{-4} bias of molecular **single scattering**.

What is haze?

Often defined by its scattering consequences

rather than by its scattering constituents

Consequences:

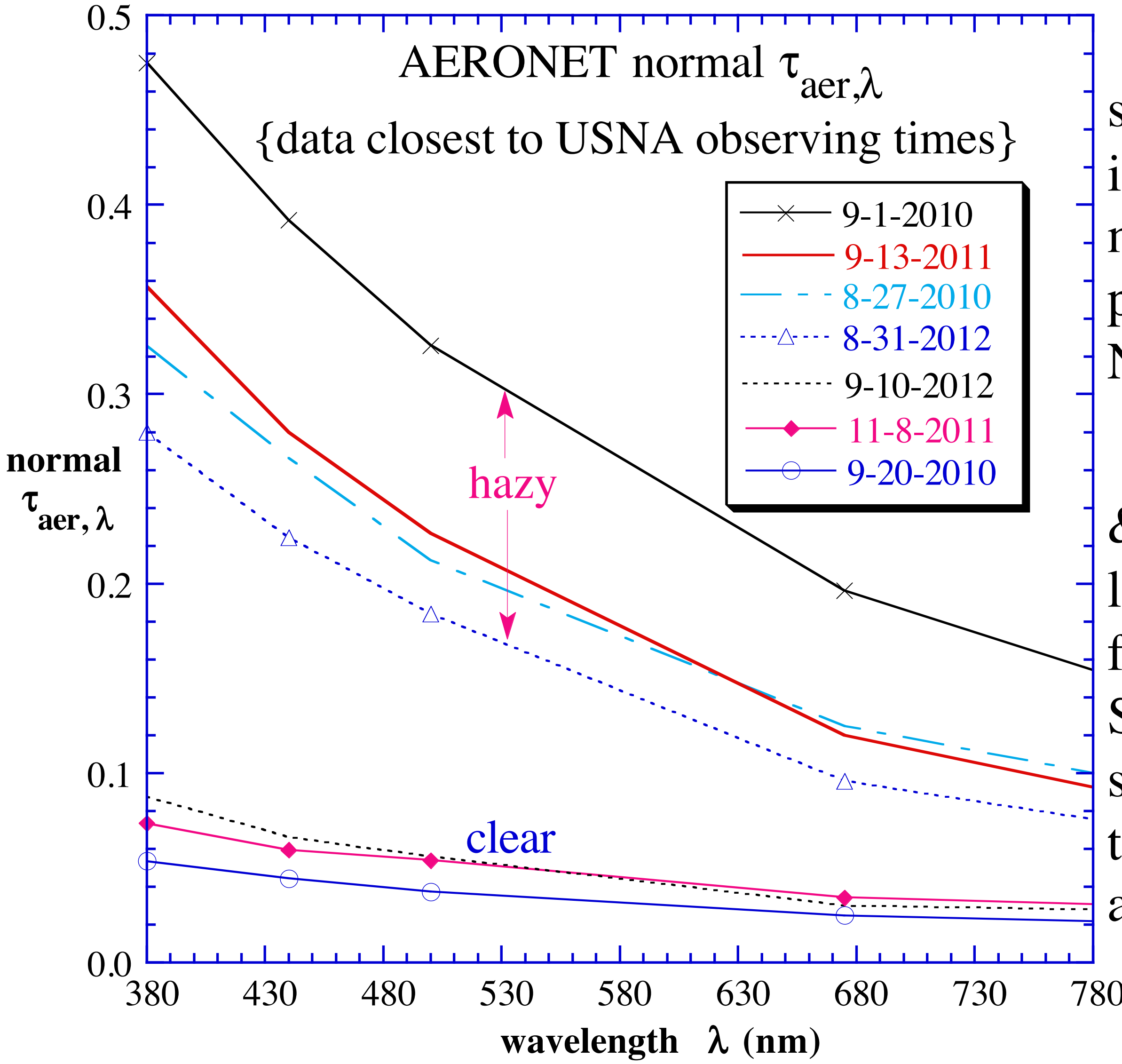
- reduced visible-λ contrast,
  especially over long physical paths
- differs only by degree from clear-sky airlight
- decreased IR albedo in upper troposphere

Constituents:

- hygroscopic aerosols (*e.g.*, sea salt,
  ammonium sulphate)
- tropospheric dust or smoke particles
- particles in photochemical smog
- in stratosphere, volcanic ash or sulfuric acid droplets

Ile d'Anticosti, Gulf of St. Lawrence, 6-16-2006

Resonon Pika II imaging spectrometer & rotation stage, both controlled by MacBook Pro laptop

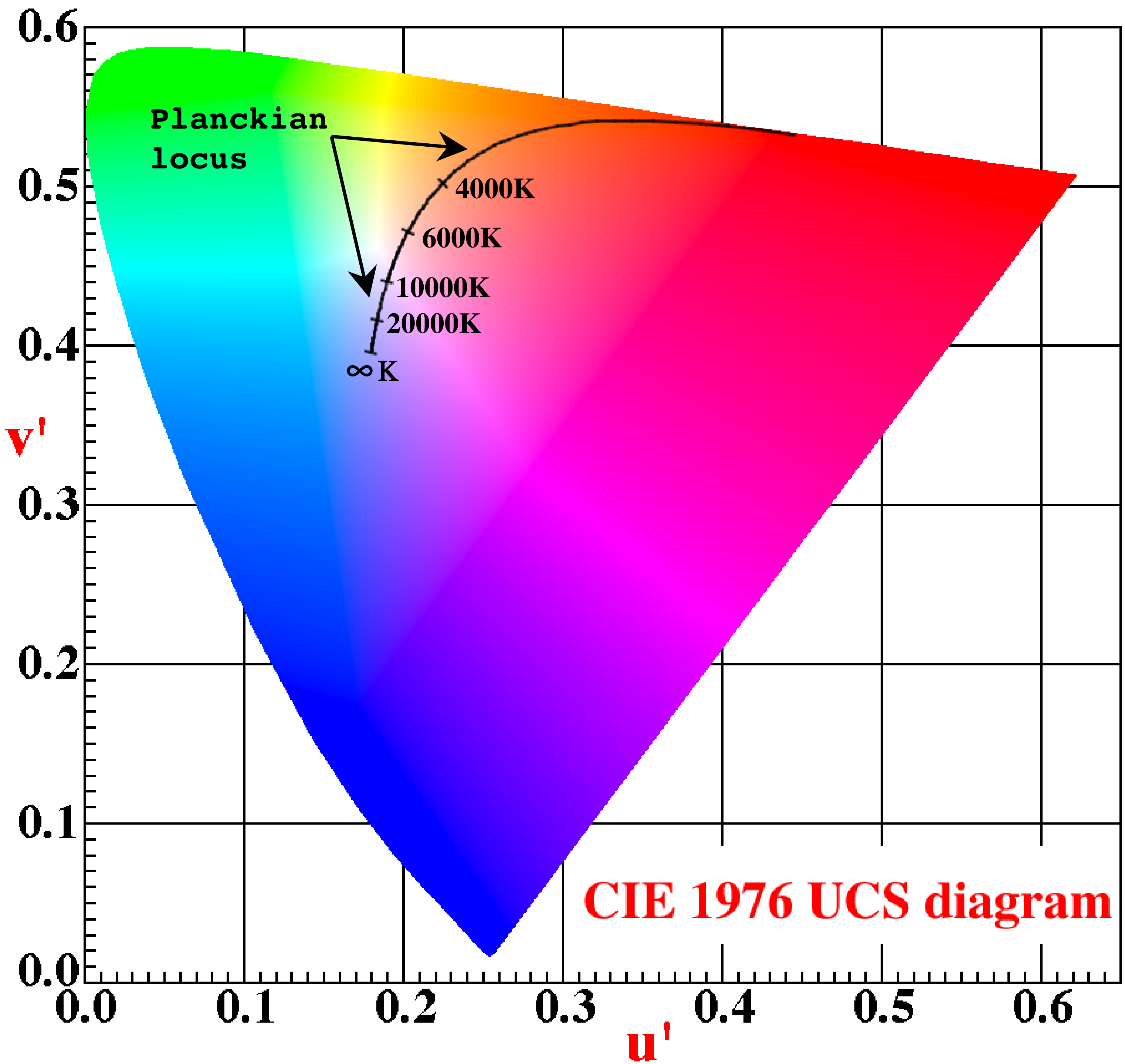


One basic measure of haze's scattering & absorption effects is aerosol optical depth $\tau_{aer,\lambda}$, measured near USNA by sun photometers of AErosol RObotic NETwork or AERONET.

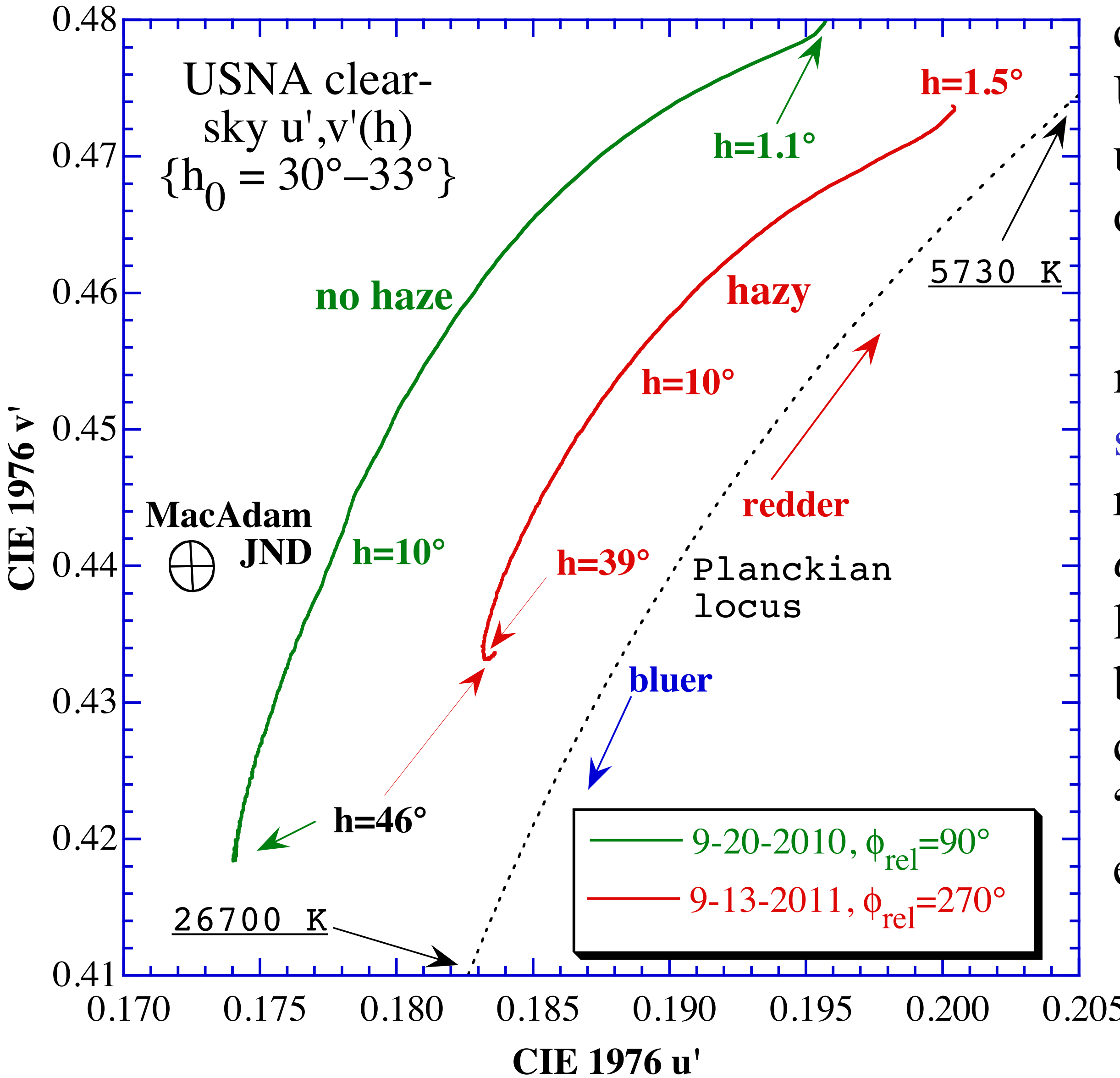
$\tau_{aer,\lambda}$ is measured at a few λ, & then interpolated by a power-law function $\tau_{\lambda} = \tau_{\lambda 0}(\lambda/\lambda_0)^{-\alpha}$ for Ångström coefficient α. So $\tau_{aer,\lambda}$ is assumed to decrease smoothly with λ, & haze starts to become visible for $\tau_{aer,\lambda} \gtrsim 0.2$ at short wavelengths.


USNA, h0 ~ 30°, 9-20-2010,
φrel = 90°, τaer(380 nm) = 0.0535


h0 ~ 33°, 9-13-2011,
φrel = 270°, τaer(380 nm) = 0.357


Planckian locus
4000K
6000K
10000K
20000K
∞K
v'
u'
0.0
0.1
0.2
0.3
0.4
0.5
0.6
CIE 1976 UCS diagram

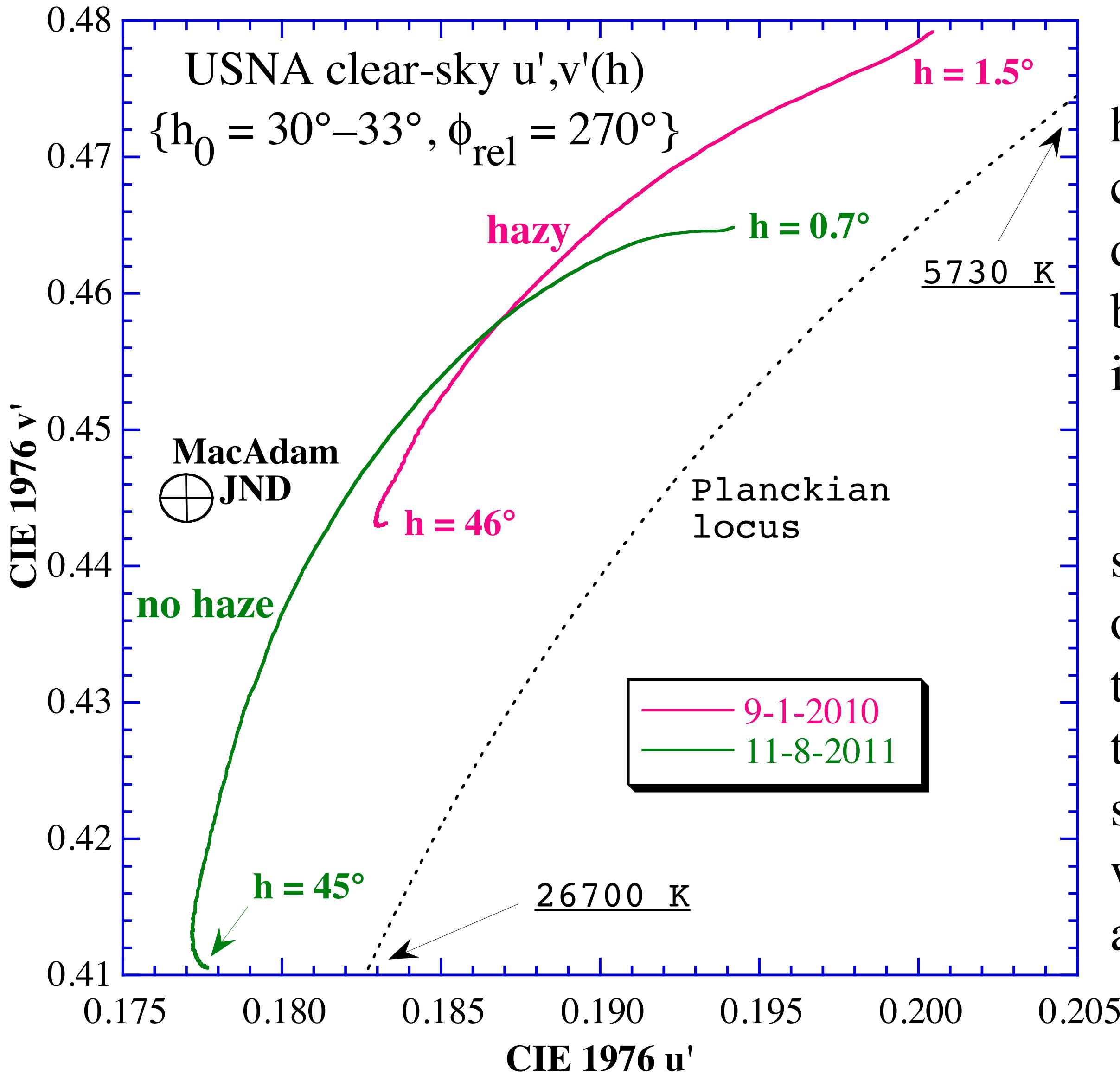
Start with some haze-related color shifts, …



To quantify USNA skylight colors, zoom into CIE 1976 UCS diagram, where we plot u´,v´ chromaticities as functions of view-elevation angle *h*.

For scans made along sky meridians at azimuth relative to sun ϕ_{rel}, on the hazy day the resulting chromaticity curve is *closer* to Planckian (blackbody) locus. Also note that **(1)** sky blueness increases with *h* in both cases, **(2)** small chromaticity "hooks" occur at low- & high-*h* ends of the hazy-sky curve, & **(3)** meridional color gamut is smaller on the hazy day.

… shifts which take several different forms.

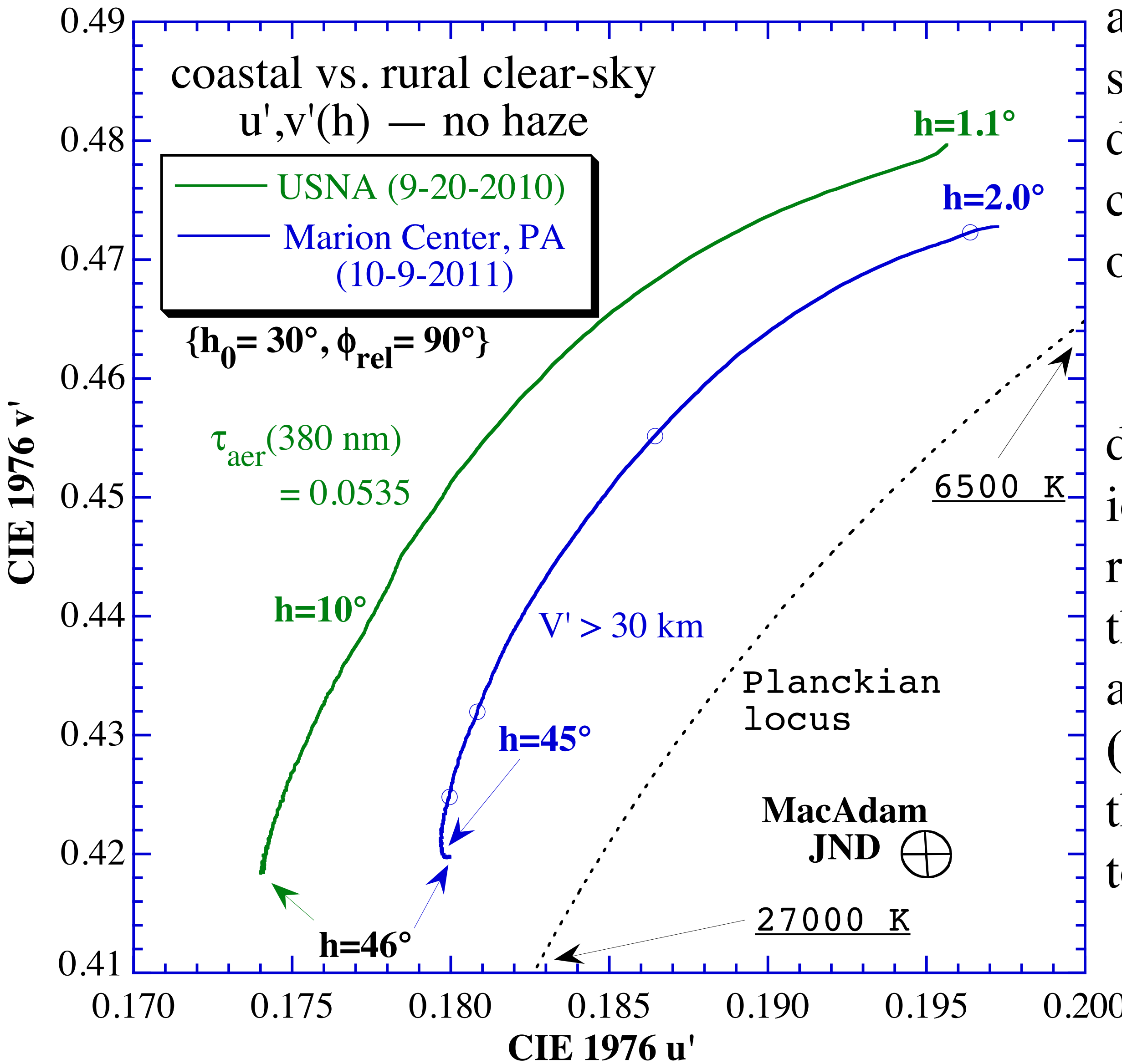


For a different pair of clear-hazy skies, meridional u´,v´(*h*) chromaticity curves are at ~ same distance from Planckian locus but with colors that differ visibly in both CCTs & overall gamuts.

In fact, only for hazy skies do such perceptible CCT shifts occur (*i.e.*, large shifts ~ parallel to Planckian locus), behavior that makes good qualitative sense — but which isn't yet well explained in terms of aerosol optics.

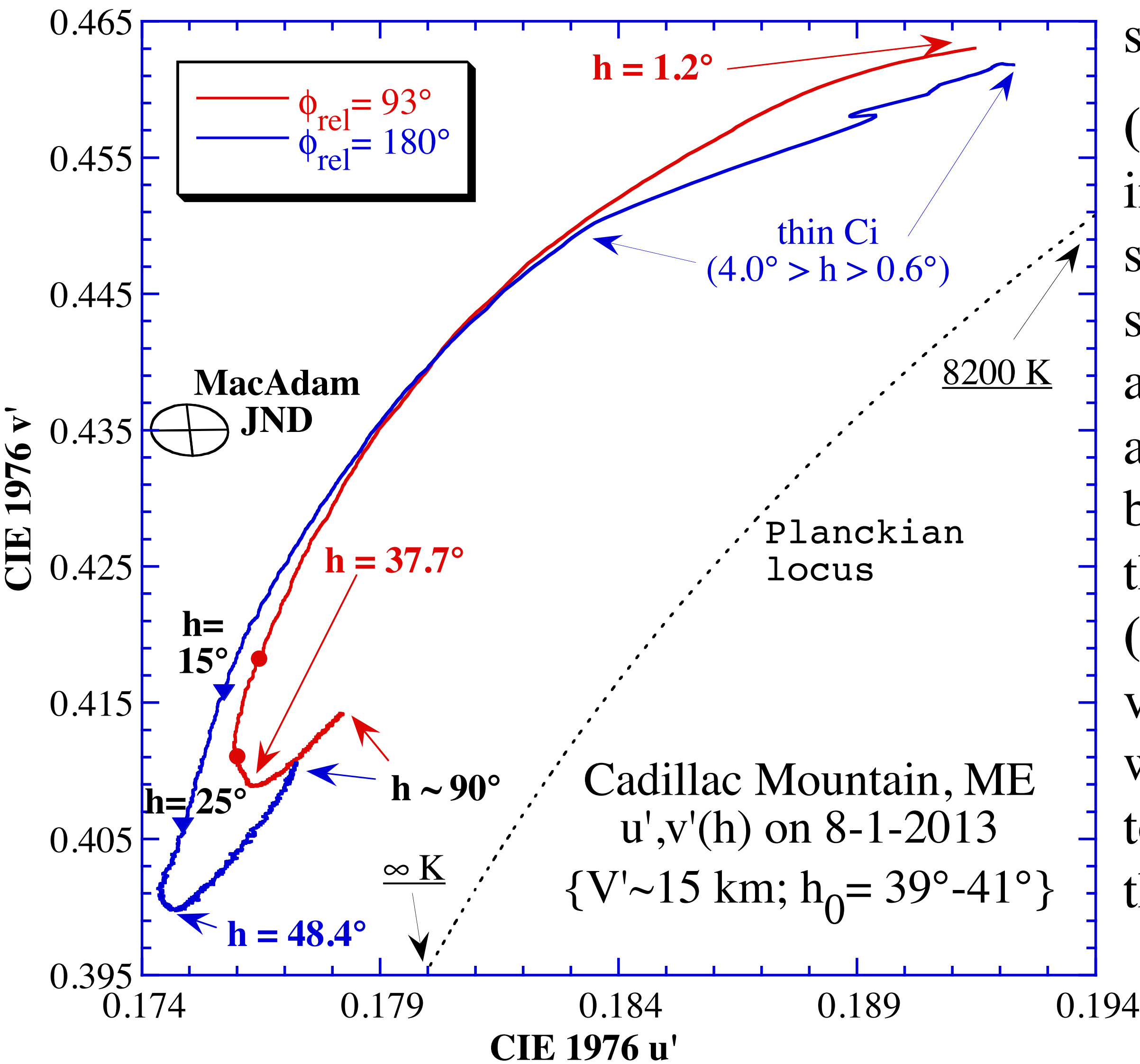

Marion Center, PA, 10-9-2011,
$h_0 \sim 30°, \phi_{rel} = 90°$


$h_0 \sim 35°, \phi_{rel} = 180°$



Certainly the *kind* as well as amount of aerosols affects sky color, & that may explain differences seen here between coastal & rural inland skies observed on 2 haze-free days.

Note that **(1)** green vegetation doesn't displace the rural Marion Center curve greenward relative to USNA, **(2)** only the rural haze-free sky has a high-*h* chromaticity hook, & **(3)** despite being visibly bluer, the rural curve is in fact *closer* to the Planckian locus, which suggests that its blues should appear less saturated.



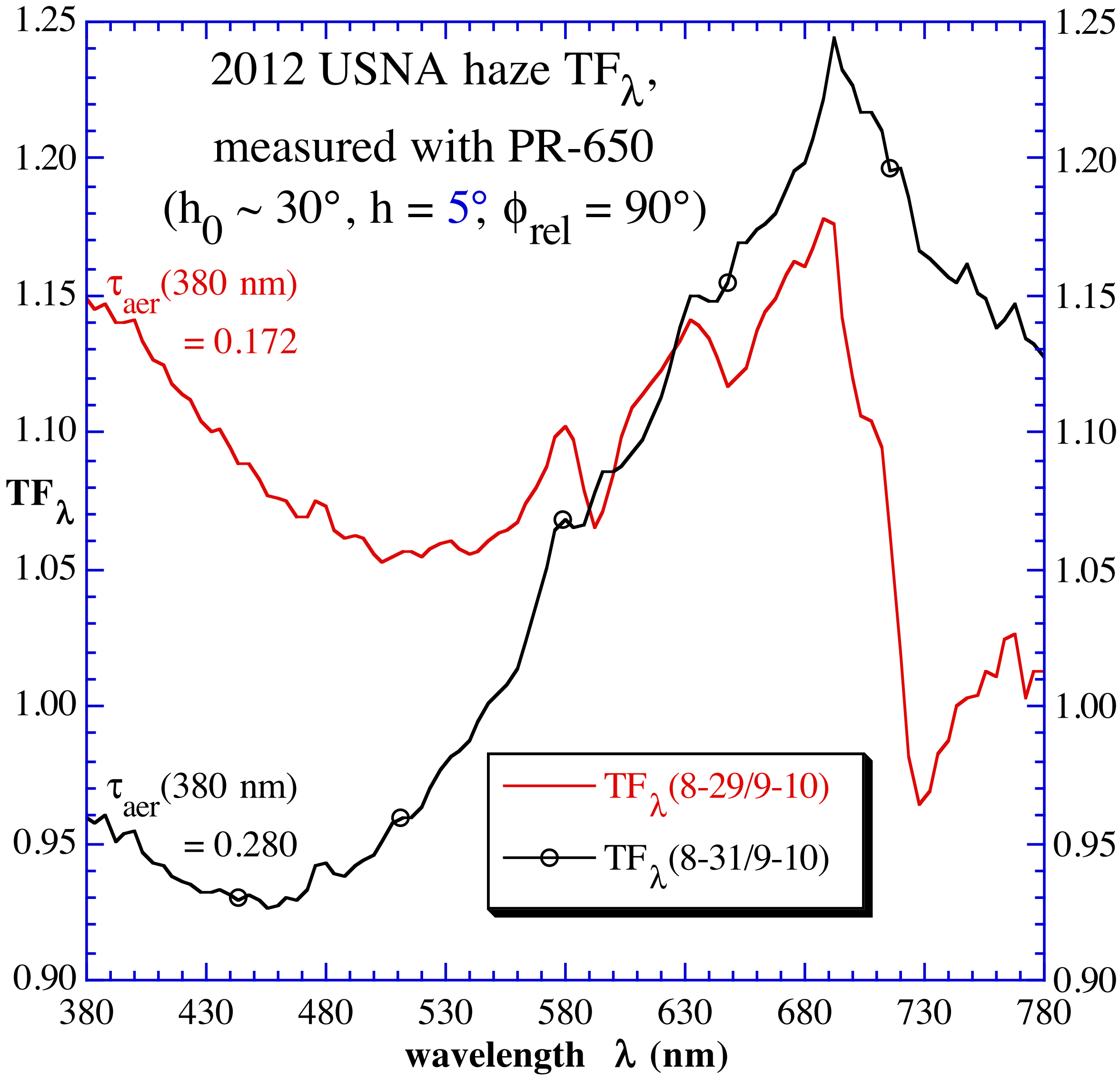
At a mountaintop site near the Atlantic Ocean, extend the clear-sky u´,v´(*h*) scans to the zenith:

(1) these show a pattern common in clear skylight: compared with sky colors at right angles to the sun (ϕ_{rel} = 90° or 270°), colors along the same sky's antisolar azimuth (ϕ_{rel} = 180°) usually are bluer at the same *h* values — *i.e.*, these colors have higher CCTs, **(2)** the bluest skylight occurs at very different *h* for these ϕ_{rel}, which several models show is due to aerosol-dependent reddening that occurs over a limited range of scattering angles Ψ, which in turn depend on *h*.

Defining a haze spectral transfer function

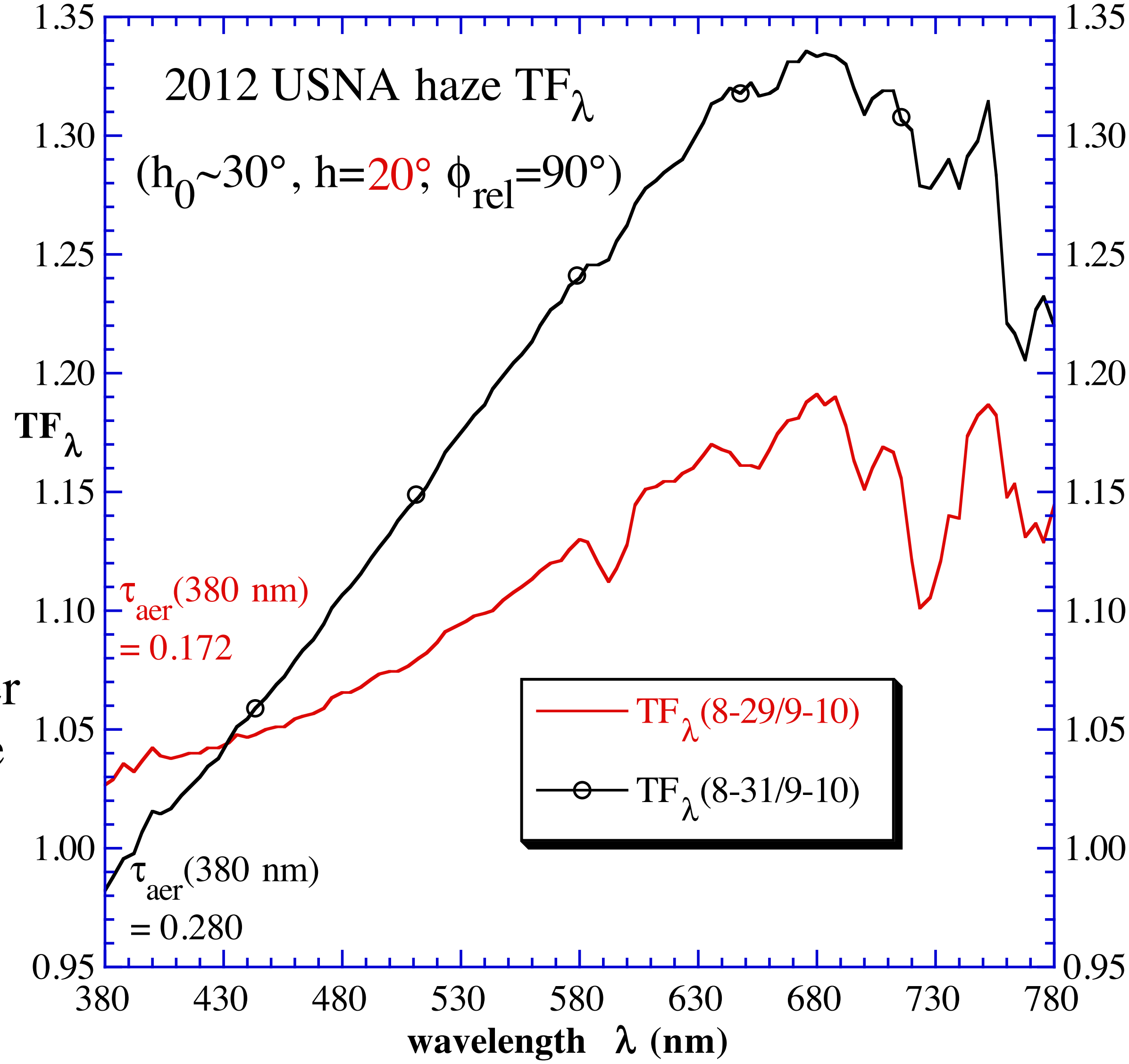
To determine haze's spectral effects at a given Ψ, calculate its spectral transfer function $TF_\lambda = L_\lambda(\text{hazy})/L_\lambda(\text{clear})$, a measure useful with L_λ from any spectrometer. TF_λ is like direct-beam transmissivity T_λ, but unlike T_λ, it often has large scattering gains (*i.e.*, $TF_\lambda > 1$).

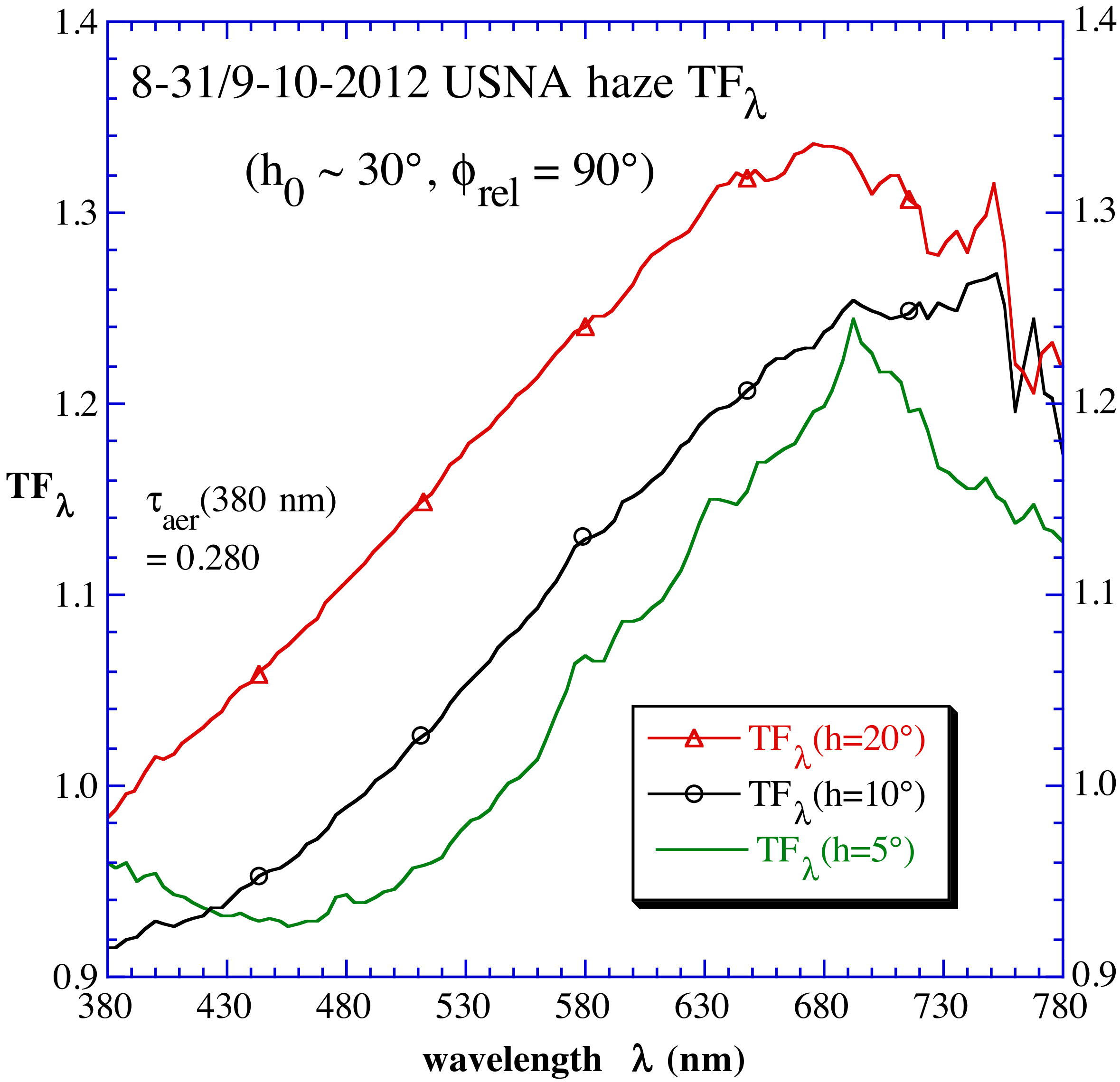
Here we use a Photo Research PR-650 to measure TF_λ near the horizon on two different hazy days, normalizing their radiances with L_λ *from a single haze-free day* (9-10-2012; its τ_{aer}(380 nm) = 0.0873).



At h = 20° & same ϕ_{rel}, the bluish haze biases seen at h = 5° are gone, replaced by near-uniform reddening at higher h for λ < 680 nm. But such reddening often only consists of *desaturating skylight blueness* at this h & Ψ.

Additionally, on 8-29-2012 the smaller τ_{aer} yields a much smaller spectral shift (*i.e.*, $TF_\lambda \sim 1$) since this sky is only slightly hazy.





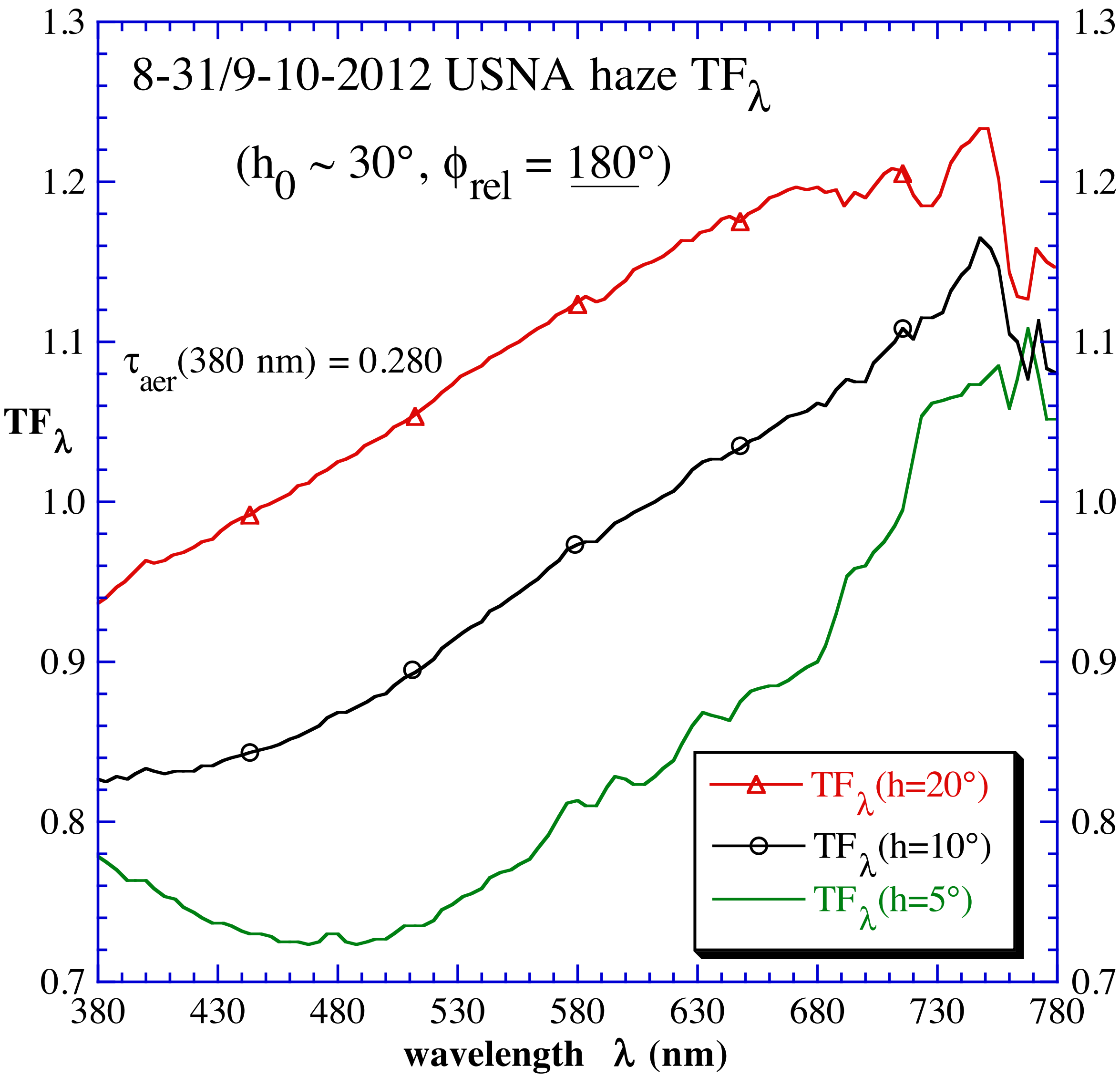
At any ϕ_{rel}, the following TF$_\lambda$ trends seem to hold:

(1) a slight bluish bias at low h disappears by h ~ 10°,

(2) with near-linear increases for $\lambda \lesssim$ 680 nm at higher h, &

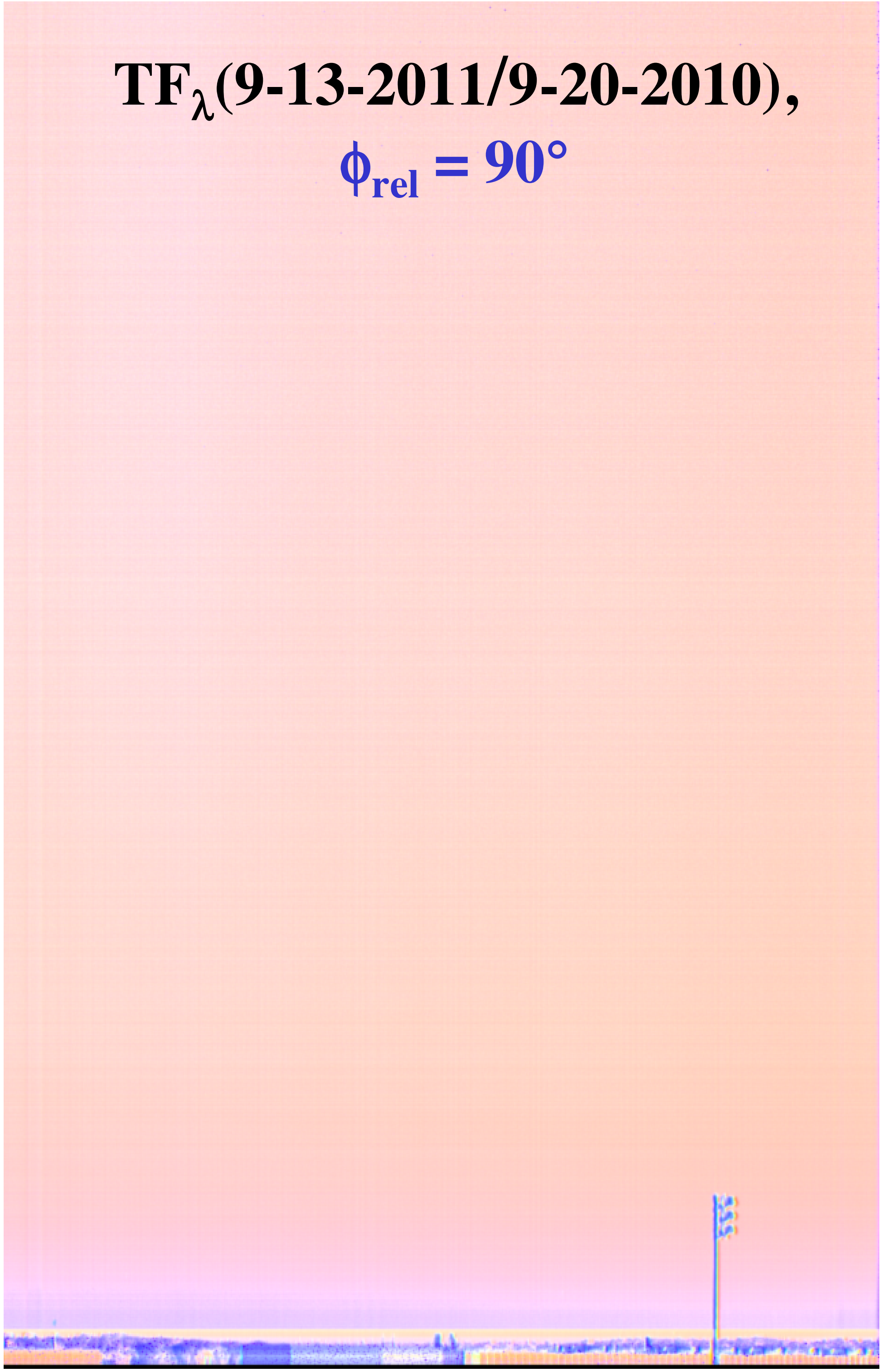
(3) decreases for $\lambda >$ 680 nm.

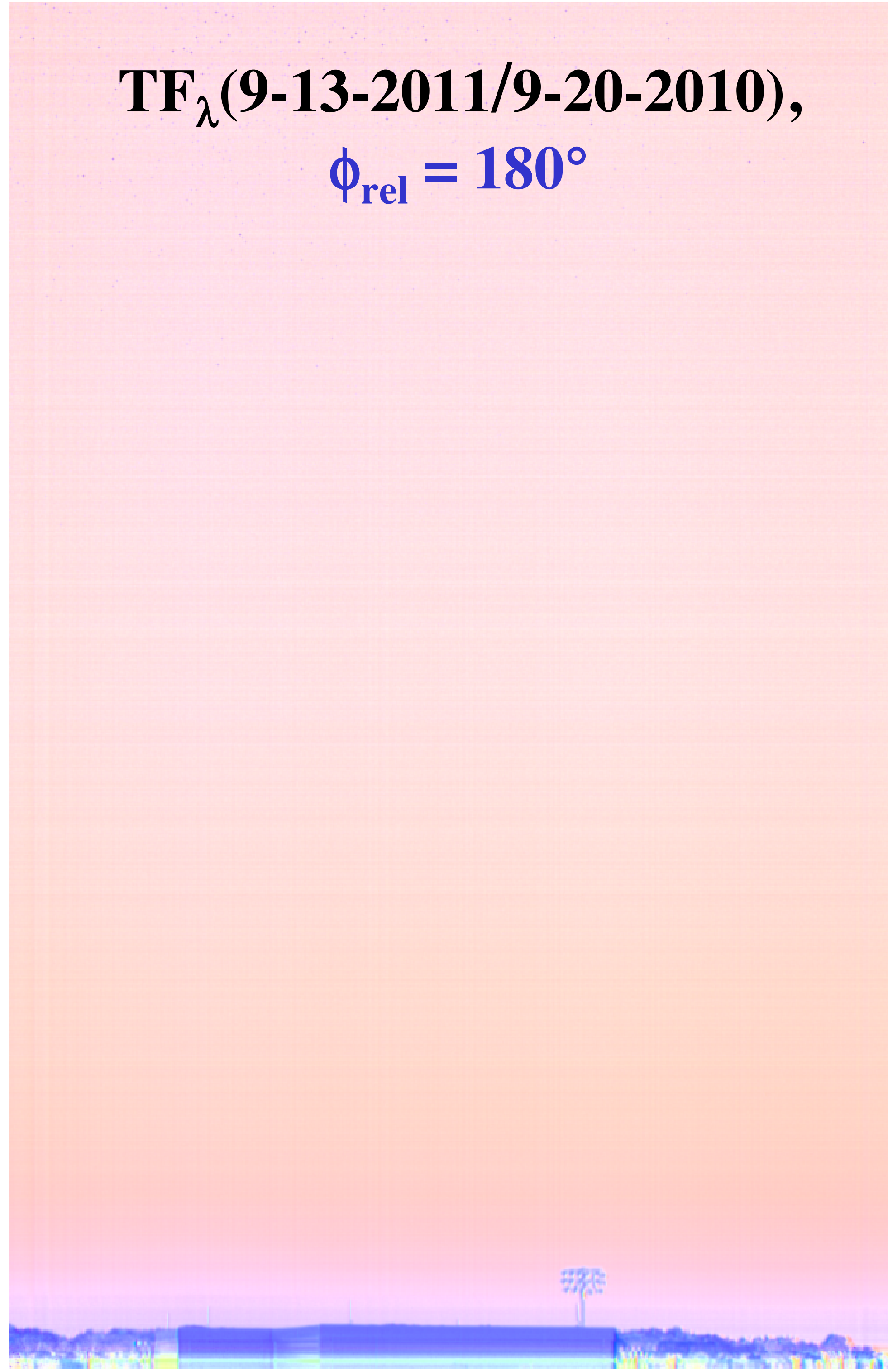
The net result? Tropospheric haze often causes an orangish shift in clear-sky colors, except near horizon where a purplish shift is likelier. Here we show results for ϕ_{rel} = 90°, but ...

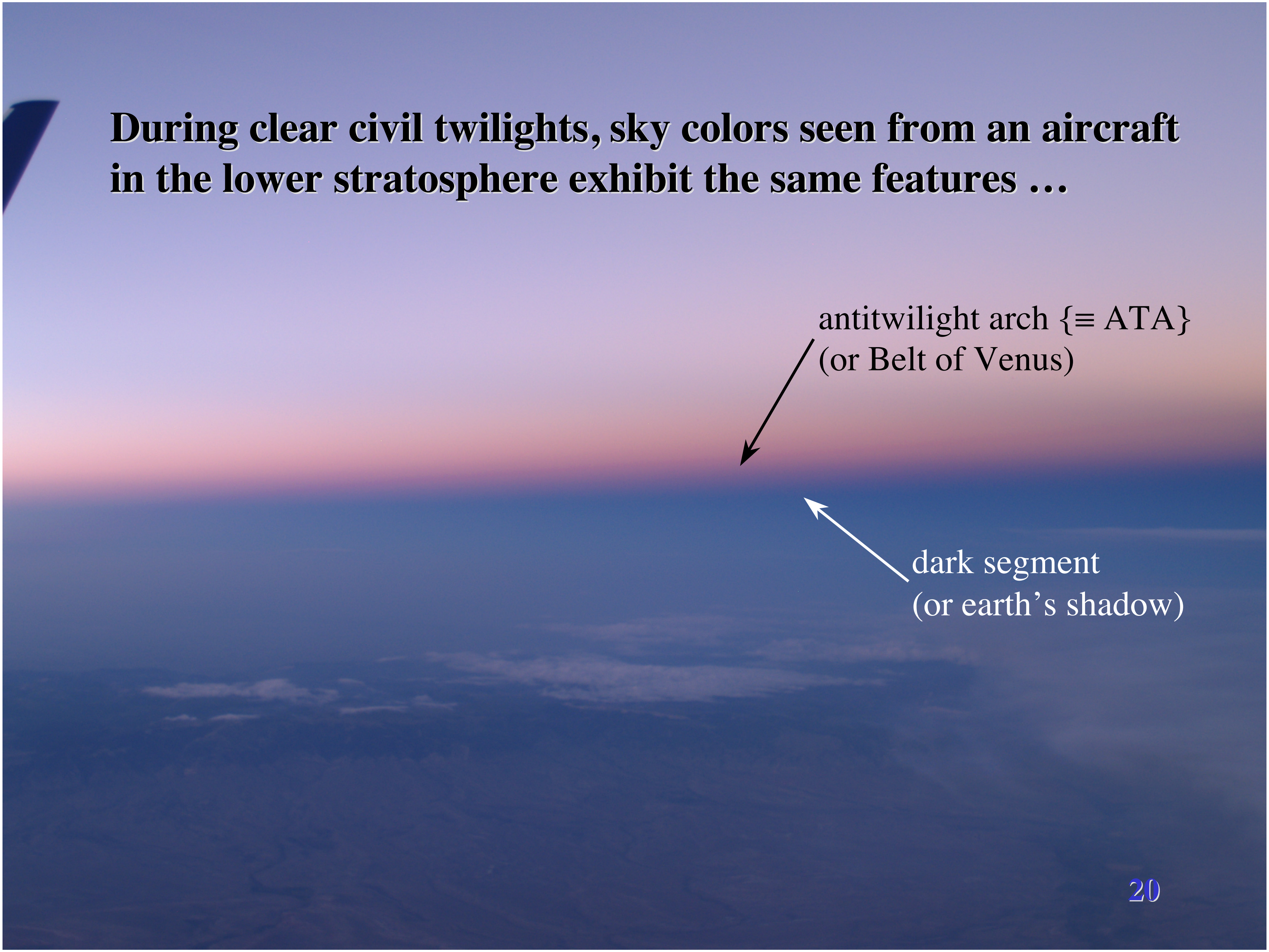


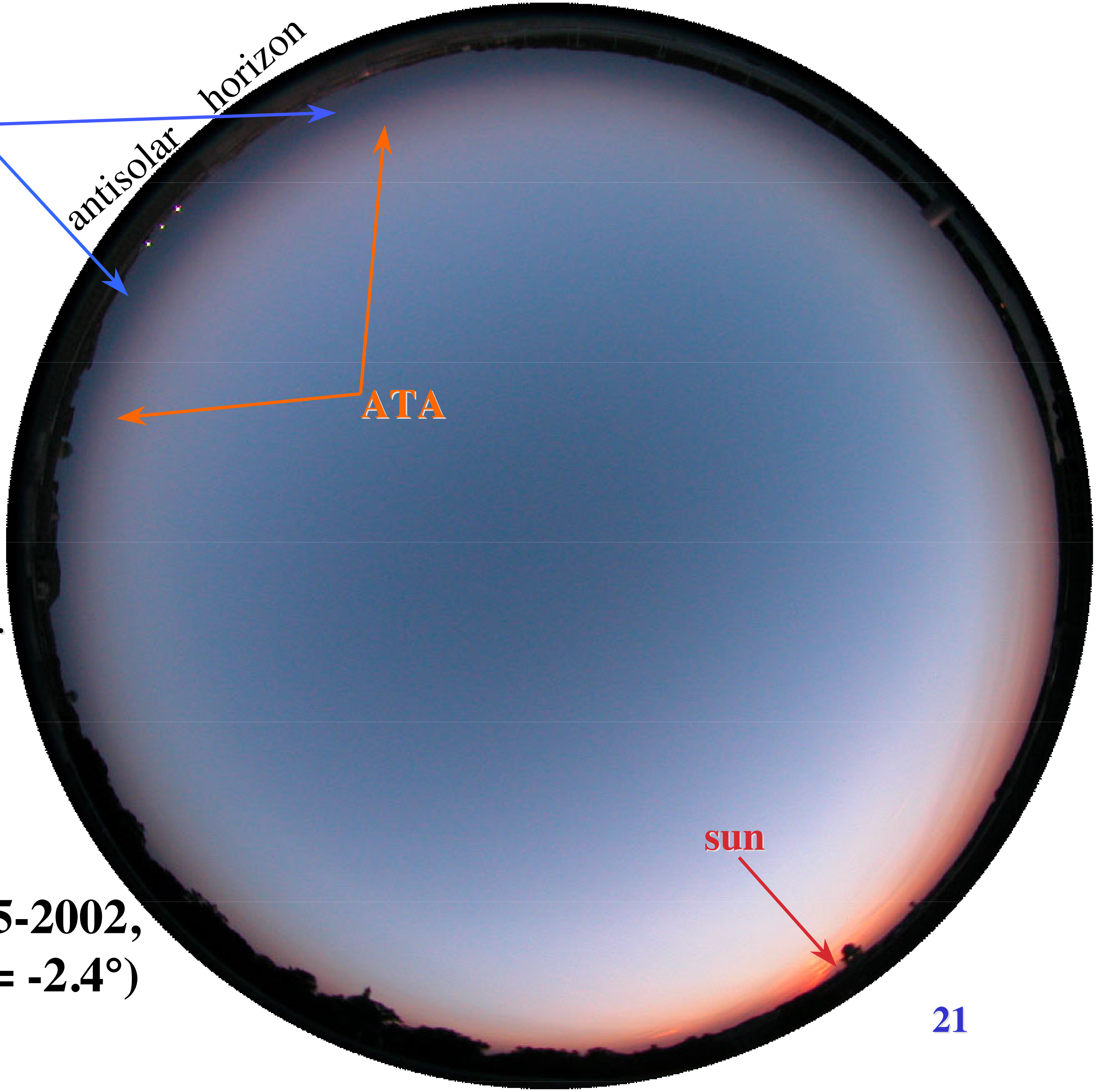
... quite similar shifts occur in the antisolar sky. Strictly speaking, these shifts also depend on h_0 & aerosol type. Obviously they will begin to disappear (*i.e.*, $TF_\lambda \rightarrow 1$) as τ_{aer} decreases.

But what might these haze-induced shifts in clear-sky colors actually *look like*?


TFλ(9-13-2011/9-20-2010),
φrel = 90°

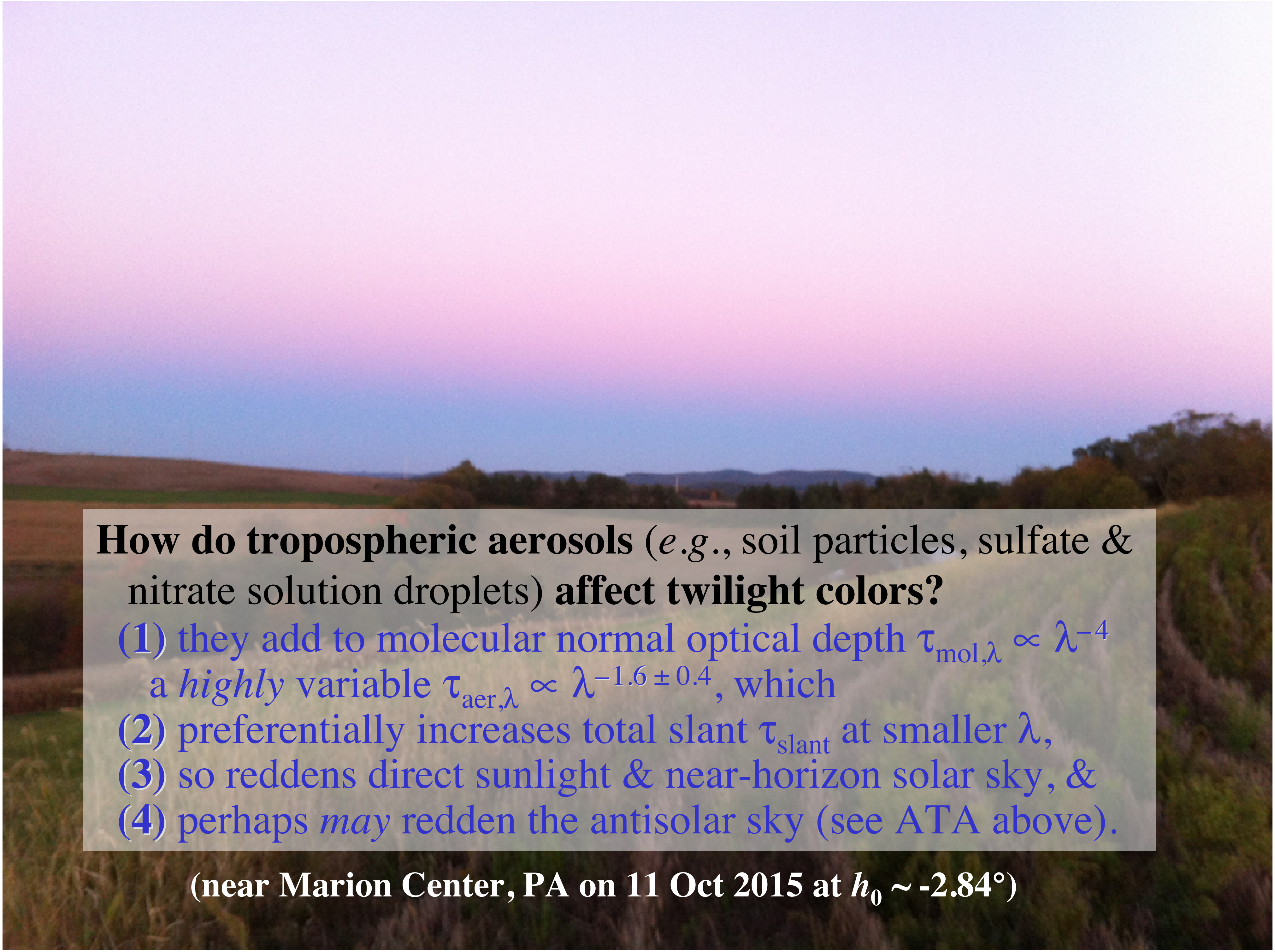

TFλ(9-13-2011/9-20-2010),
φrel = 180°

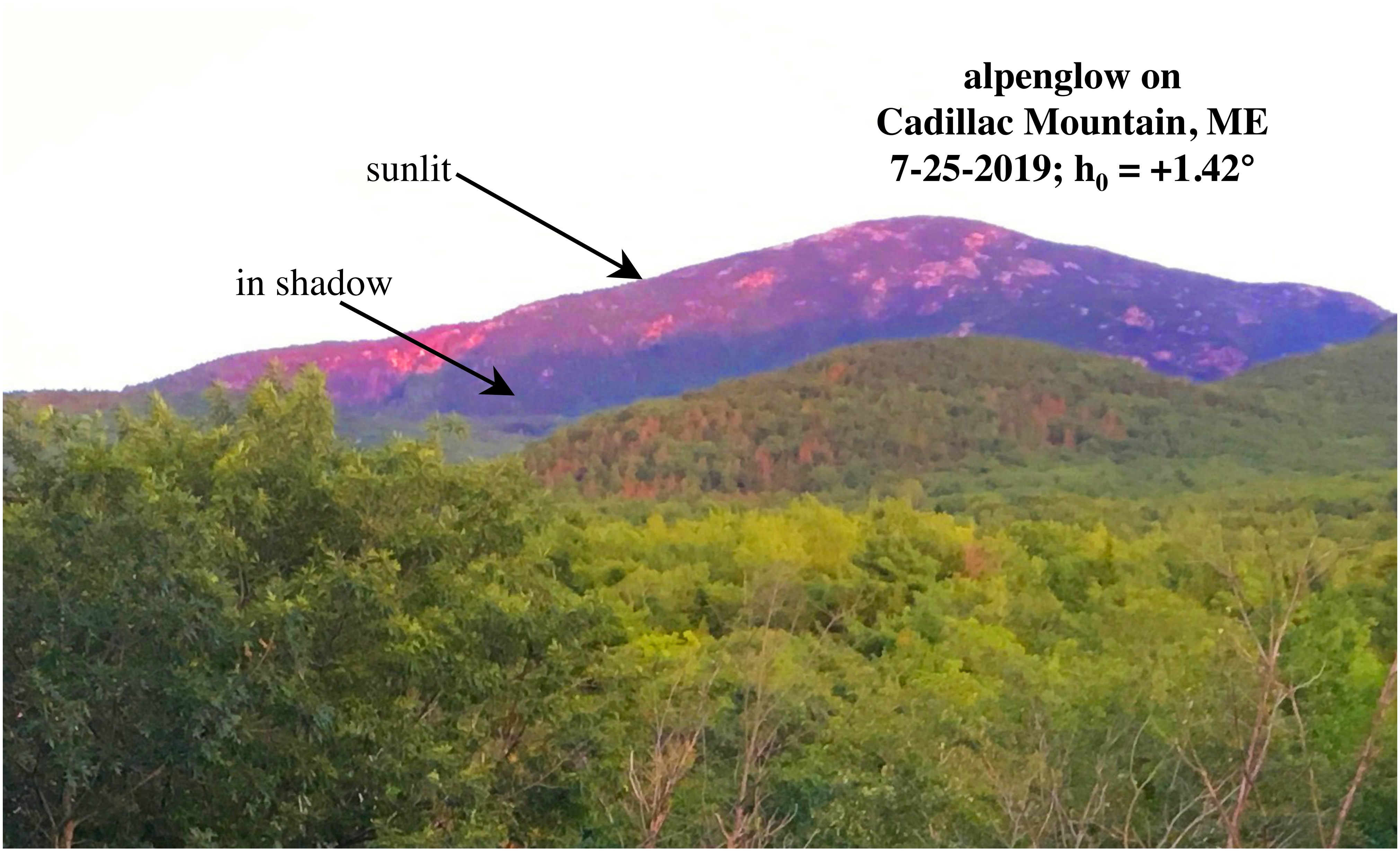

During clear civil twilights, sky colors seen from an aircraft in the lower stratosphere exhibit the same features …
antitwilight arch {≡ ATA}
(or Belt of Venus)
dark segment
(or earth’s shadow)
20



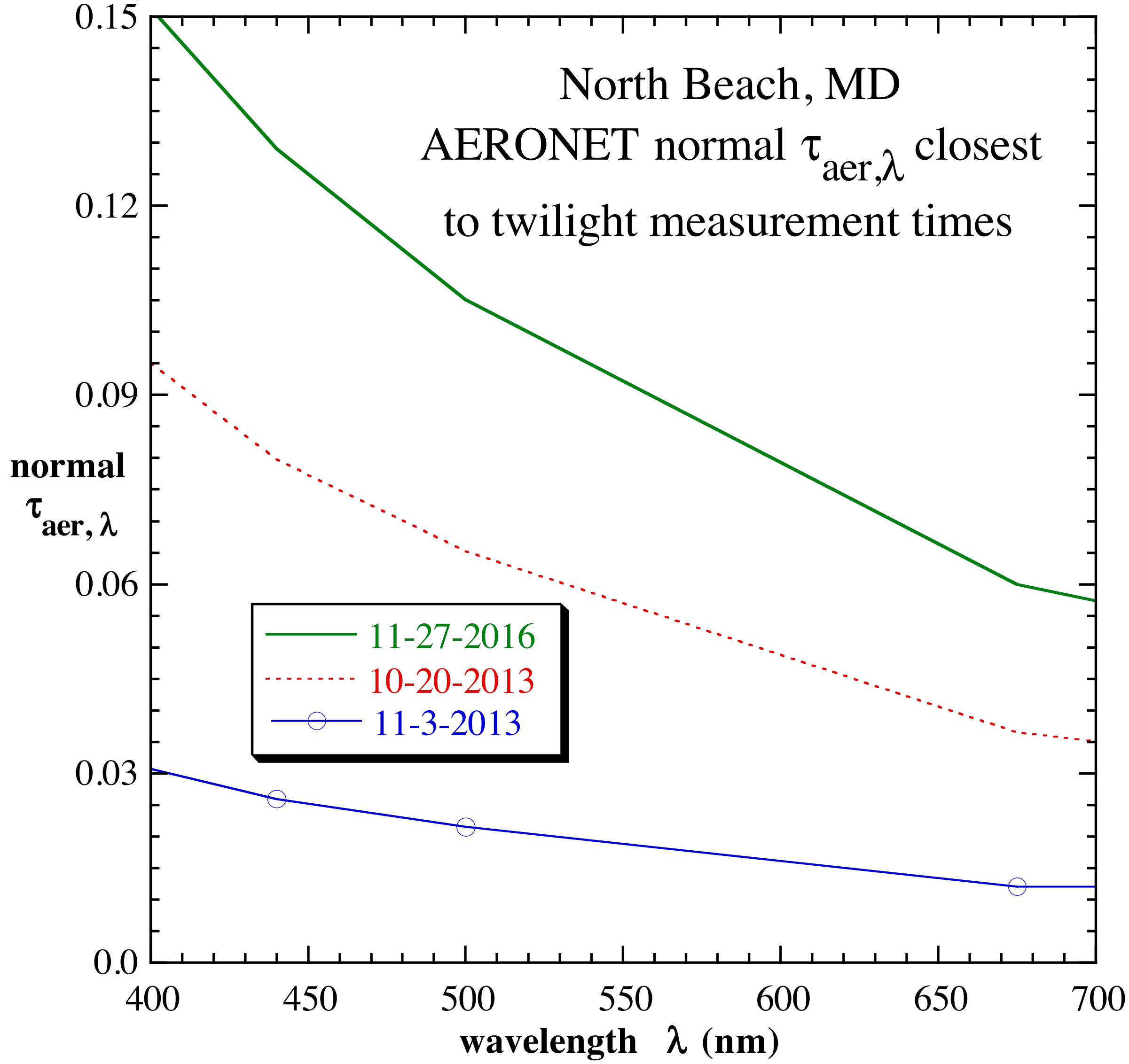
… as seen at the earth's surface, all caused by the *combined* effects of molecular & aerosol scattering.

(USNA, 9-5-2002, h_0 = -2.4°)

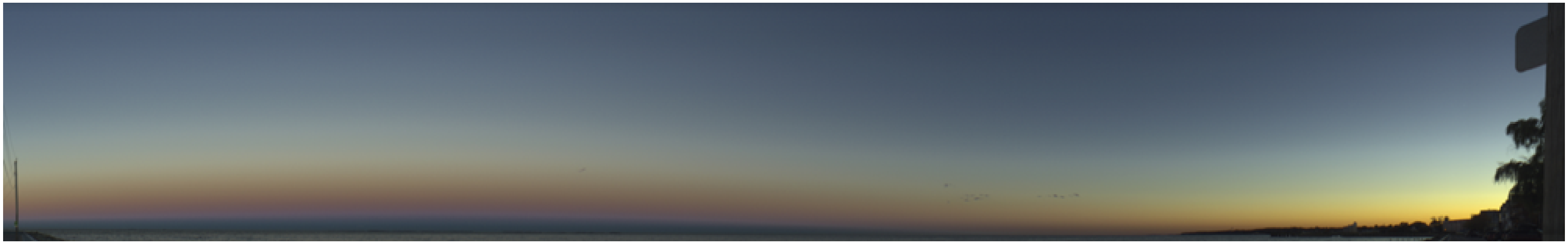

How do tropospheric aerosols (*e.g.*, soil particles, sulfate & nitrate solution droplets) **affect twilight colors?**
(1) they add to molecular normal optical depth $\tau_{mol,\lambda} \propto \lambda^{-4}$ a *highly* variable $\tau_{aer,\lambda} \propto \lambda^{-1.6 \pm 0.4}$, which
(2) preferentially increases total slant τ_{slant} at smaller λ,
(3) so reddens direct sunlight & near-horizon solar sky, &
(4) perhaps *may* redden the antisolar sky (see ATA above).
(near Marion Center, PA on 11 Oct 2015 at h_0 ~ -2.84°)



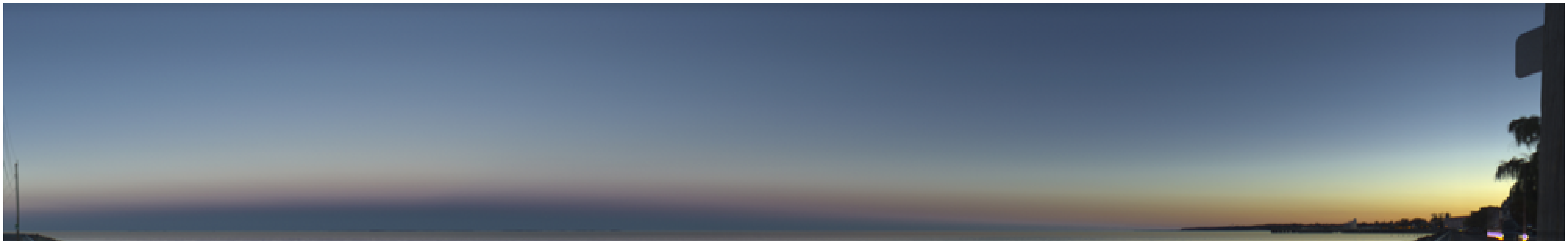
Aerosol reddening of direct sunlight can make the alpenglow redder, so might it redden antisolar twilight colors too?


North Beach, MD
AERONET normal $\tau_{aer,\lambda}$ closest
to twilight measurement times
normal
$\tau_{aer,\lambda}$
0.15
0.12
0.09
0.06
0.03
0.0
400
450
500
550
600
650
700
wavelength λ (nm)
11-27-2016
10-20-2013
11-3-2013

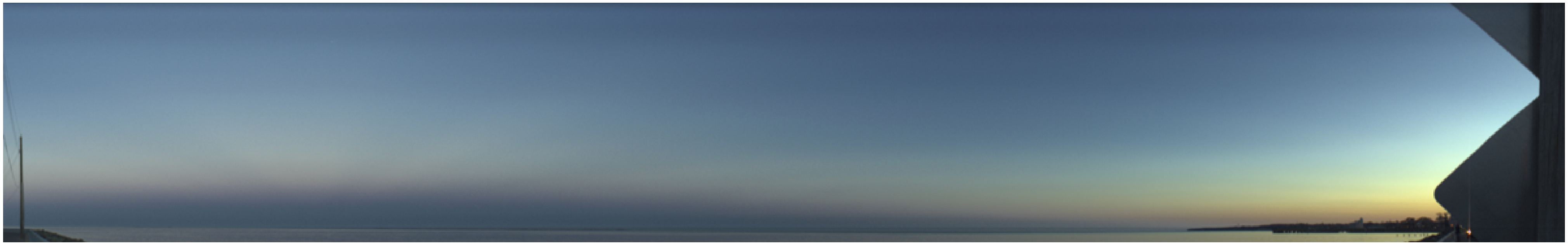
antitwilight colors at North Beach, MD



11-3-2013; $h_0 = -1.56°$; $\tau_{aer}(380\ nm) = 0.0332$ {minimum}

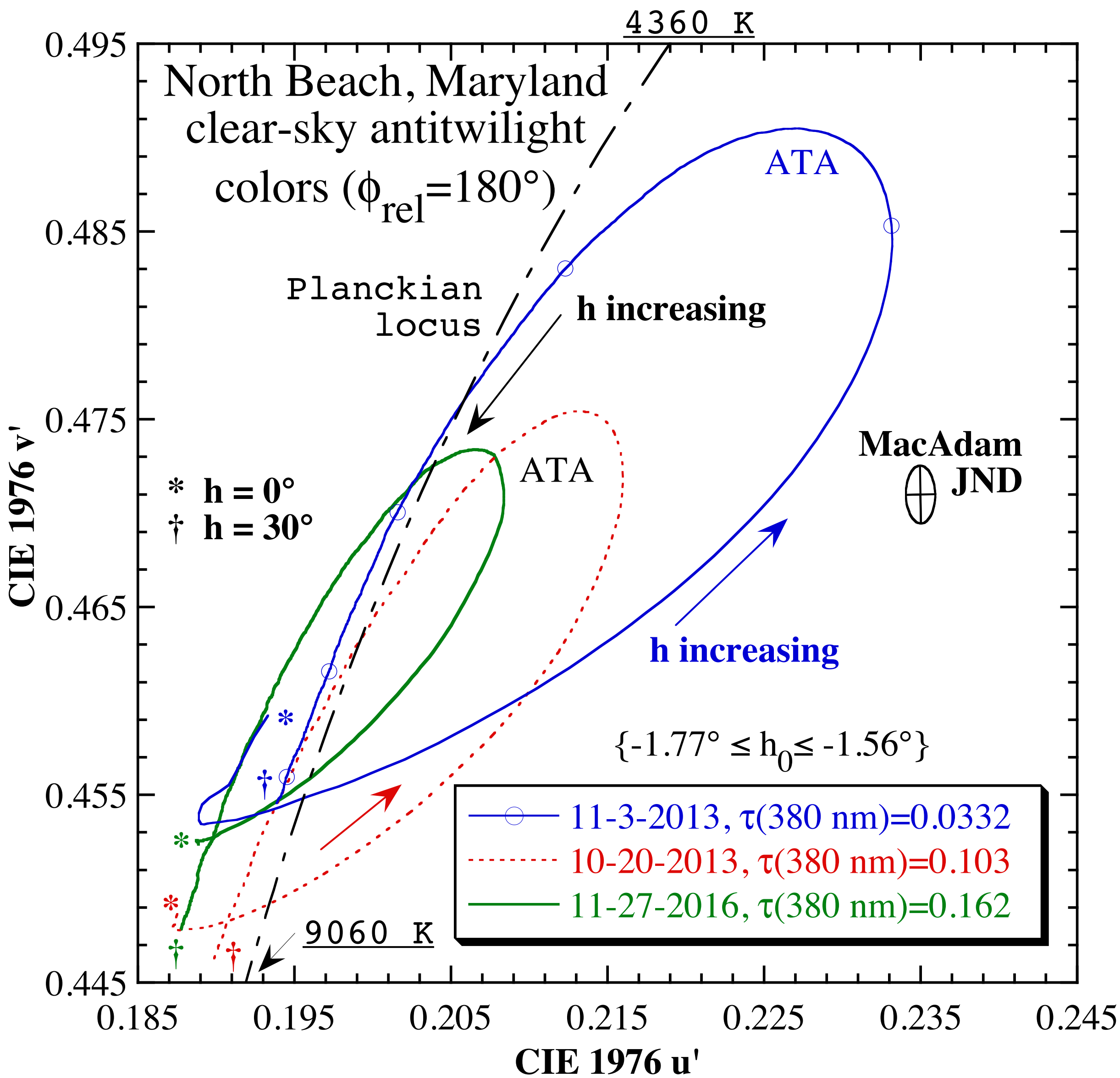


10-20-2013; $h_0 = -1.77°$; $\tau_{aer}(380\ nm) = 0.103$ {intermediate}

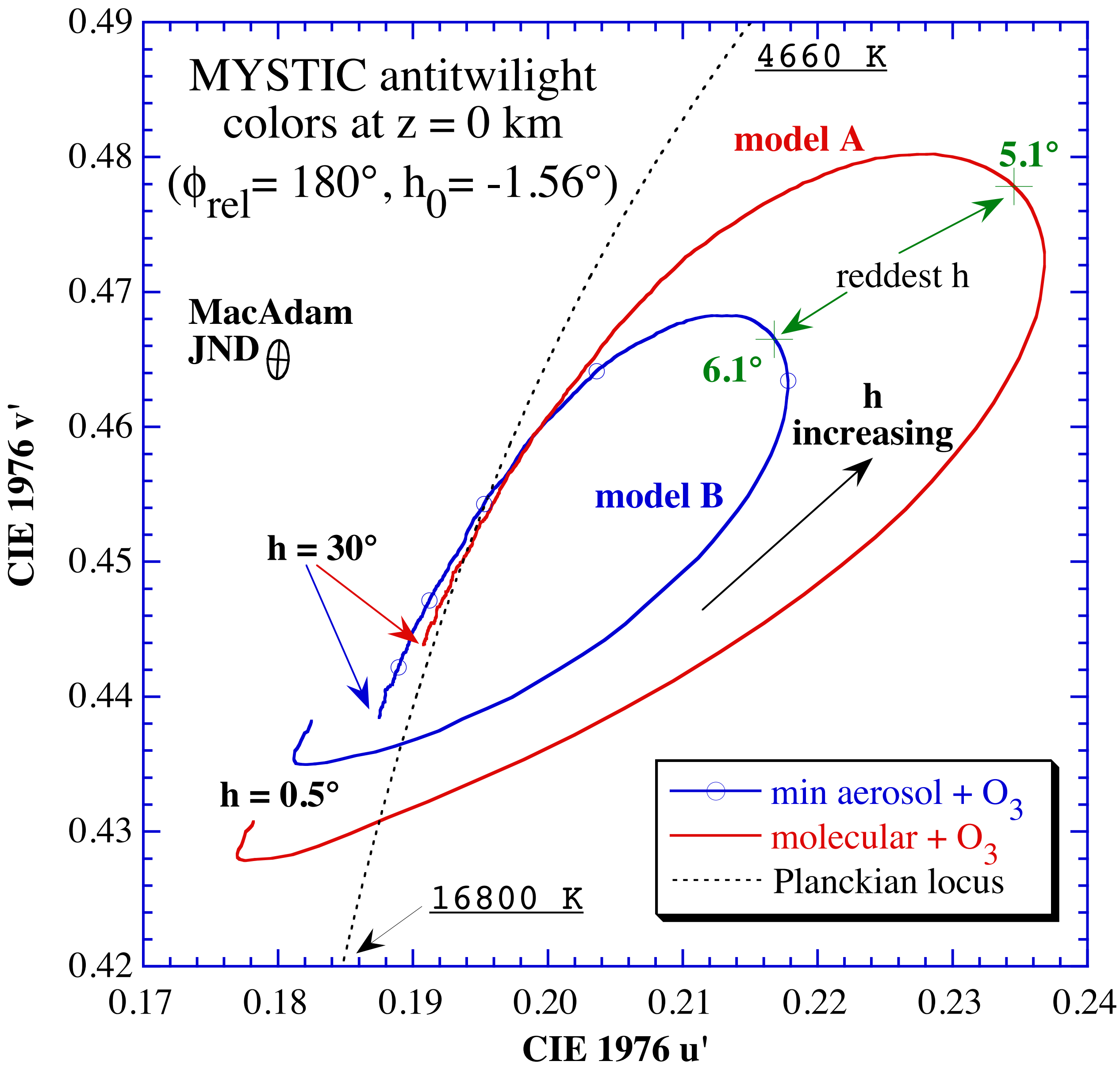


11-27-2016; $h_0 = -1.74°$; $\tau_{aer}(380\ nm) = 0.162$ {maximum}

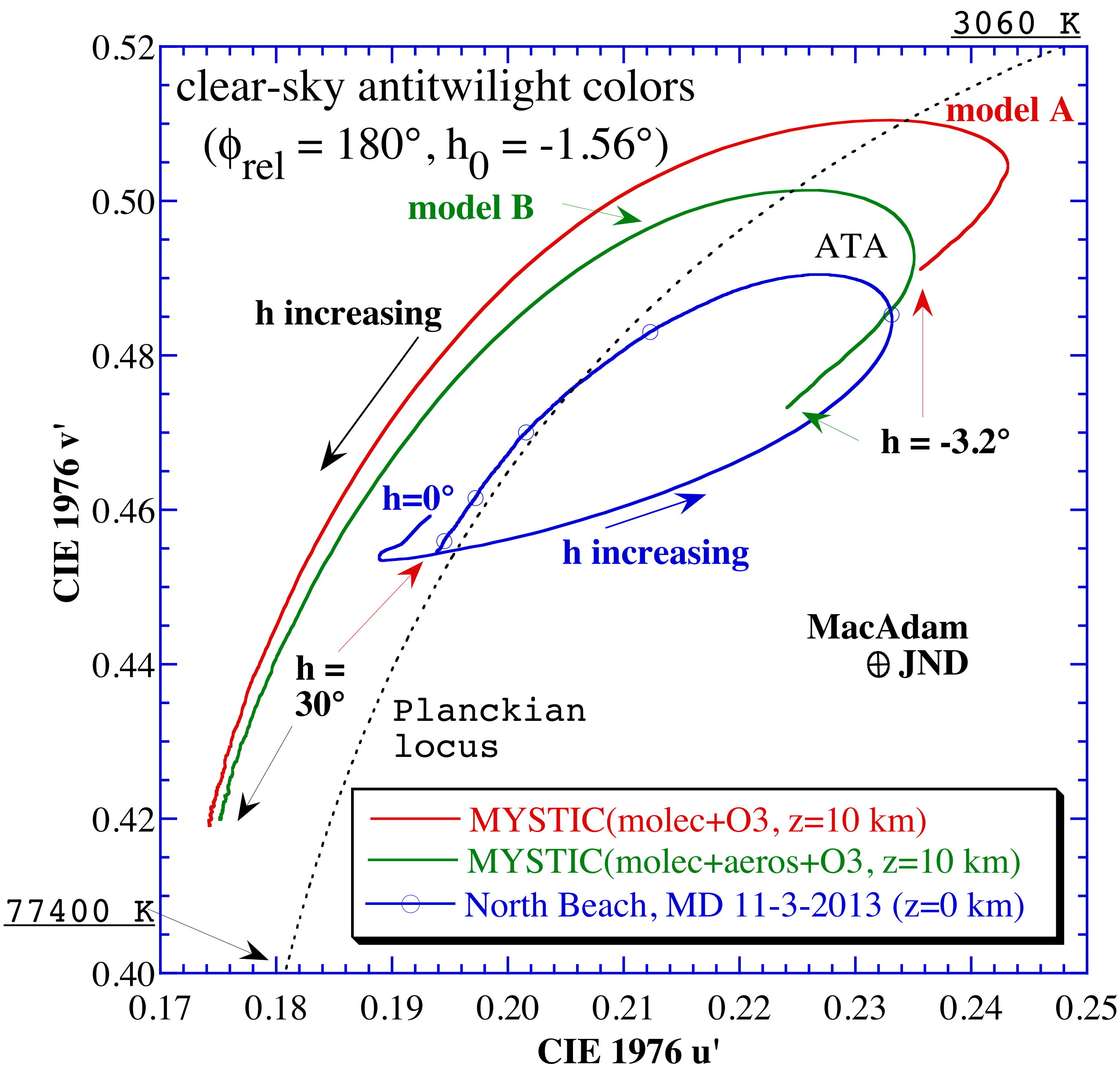
Start with hyperspectral measurements of actual antitwilight colors at the surface ($z = 0$ km) as $f(h, \tau_{aer,\lambda})$.



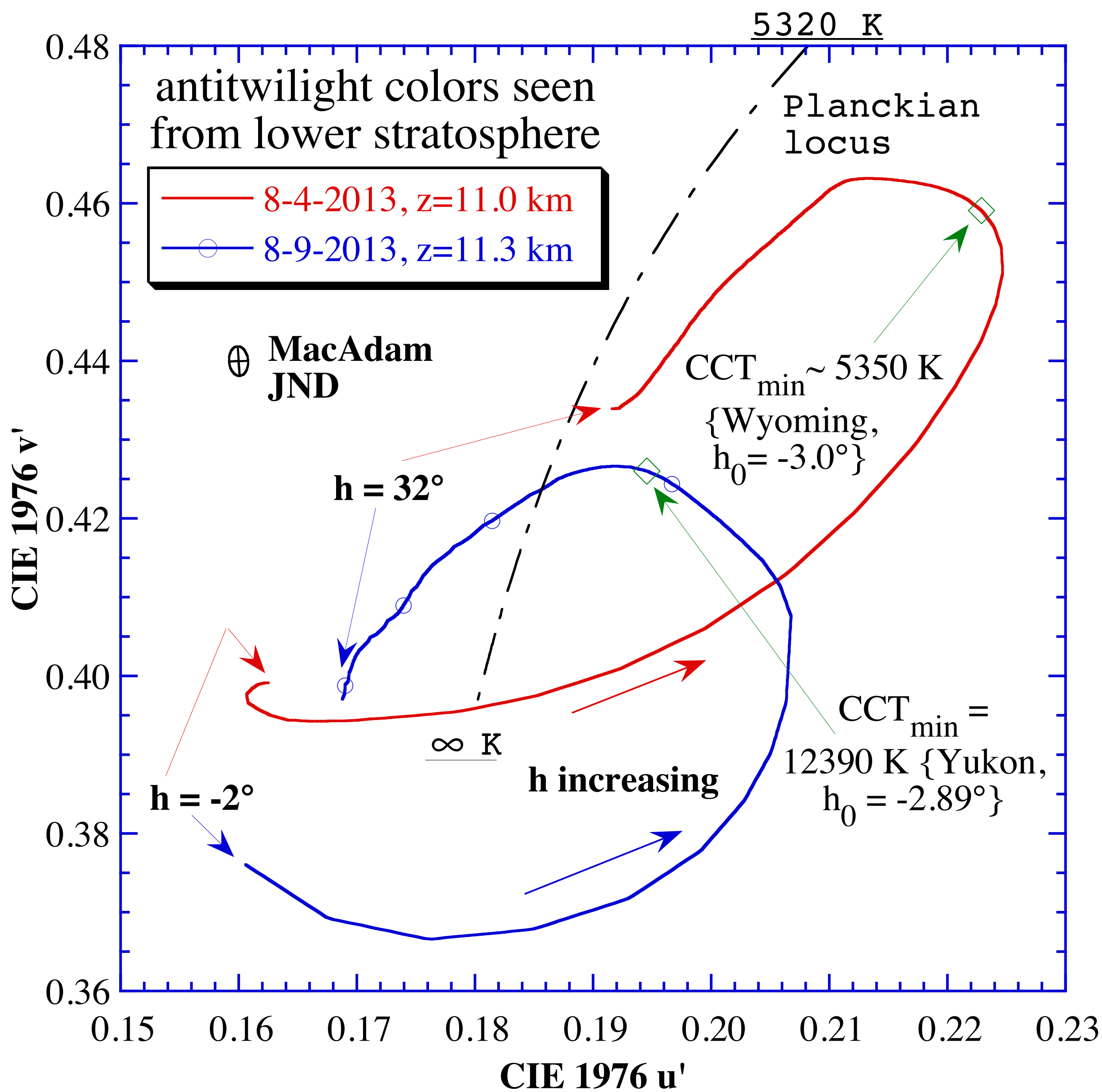
Monte Carlo modeling (MYSTIC) suggests that any amount of tropospheric aerosol will reduce gamut & vividness of surface-based antitwilight colors.

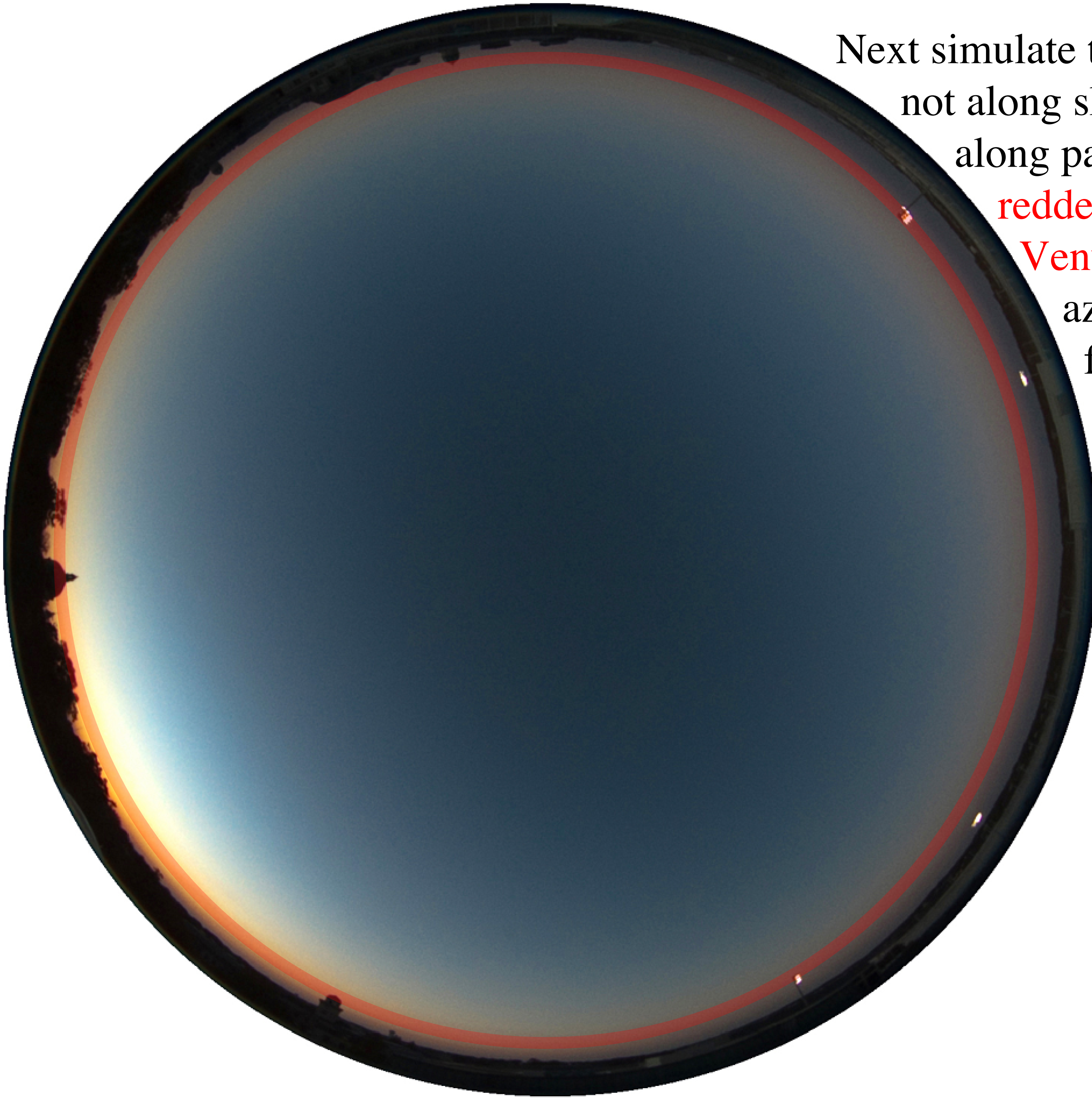


How can we make antitwilight colors even more vivid?
MYSTIC model suggests moving to the lower stratosphere.



To measure these more vivid colors, photograph the antitwilight sky at $z > 10$ km. Now antitwilight colors are produced by $\tau_{slant} \ll \tau_{slant}(0\text{ km})$ because here most backscattering paths are above the troposphere.

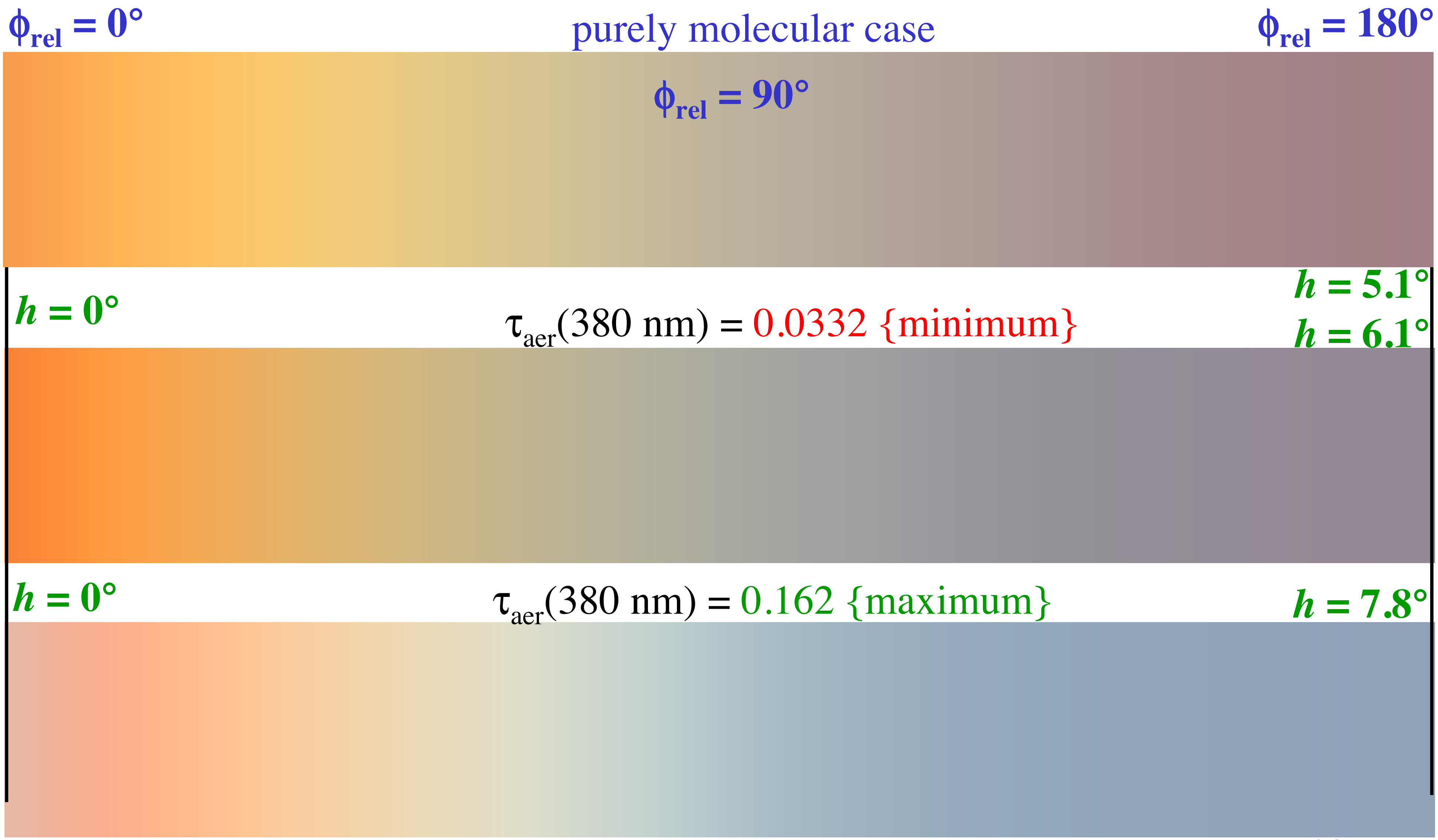

antitwilight colors seen from lower stratosphere
8-4-2013, z=11.0 km
8-9-2013, z=11.3 km
5320 K
Planckian locus
MacAdam JND
CCT$_{min}$ ~ 5350 K {Wyoming, h_0 = -3.0°}
h = 32°
CCT$_{min}$ = 12390 K {Yukon, h_0 = -2.89°}
∞ K
h increasing
h = -2°
CIE 1976 v'
CIE 1976 u'
0.48
0.46
0.44
0.42
0.40
0.38
0.36
0.15
0.16
0.17
0.18
0.19
0.20
0.21
0.22
0.23



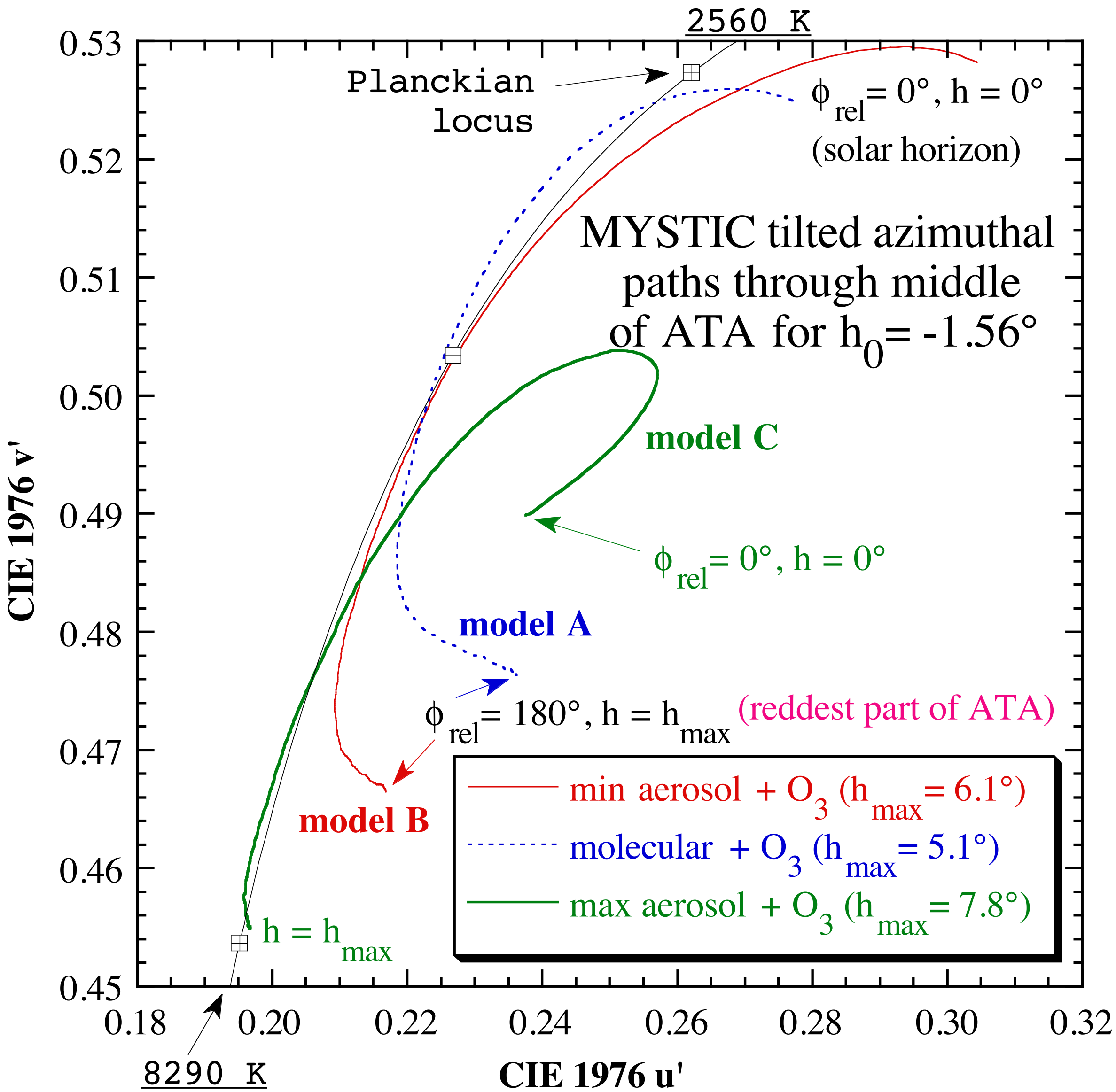
Next simulate twilight colors not along sky meridians, but along paths through the reddest part of the Belt of Venus – *i.e.*, along tilted azimuthal paths that follow celestial small circles.

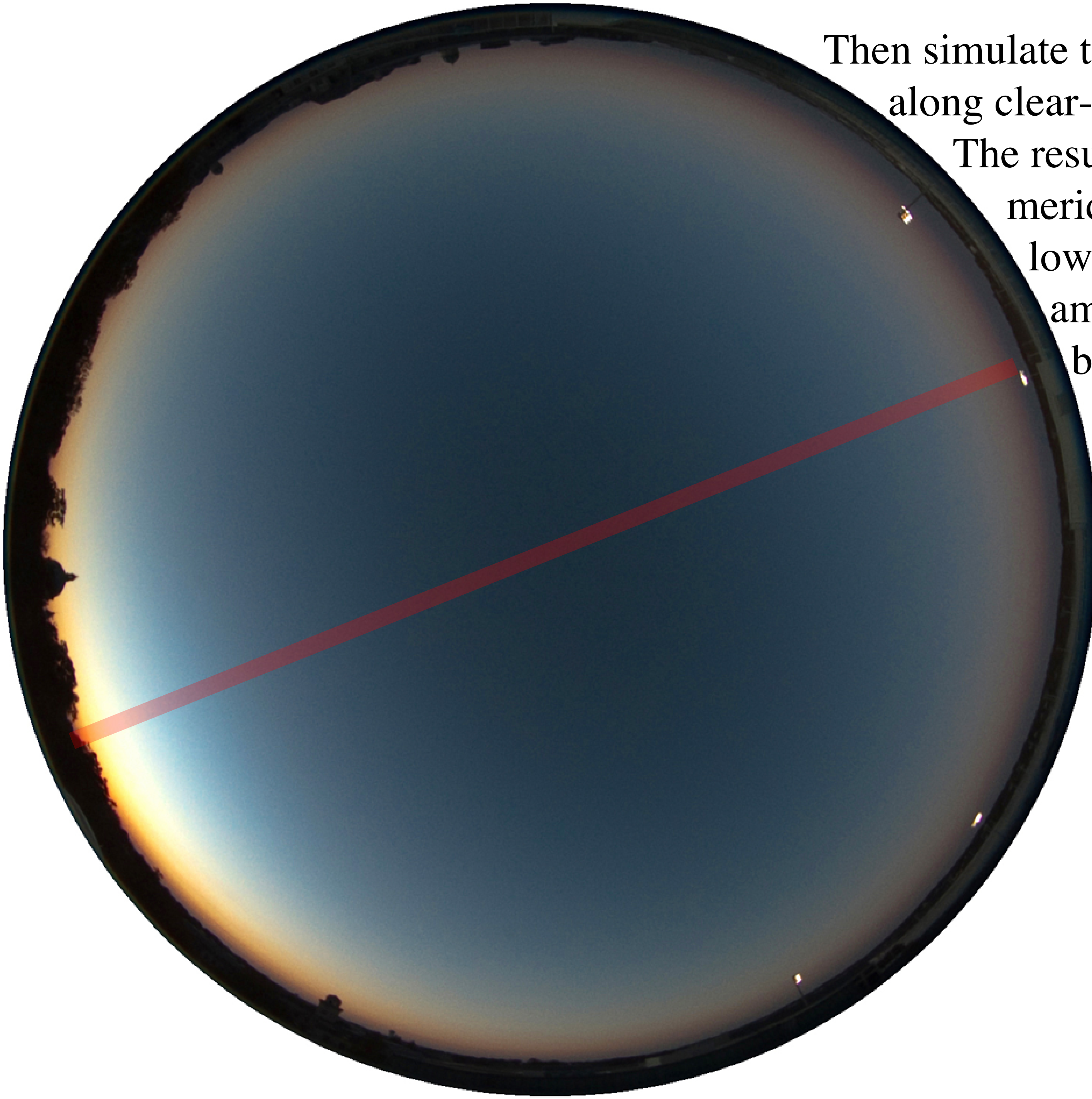
MYSTIC tilted azimuthal colors

$h_0 = -1.56°$, $z = 0$ km



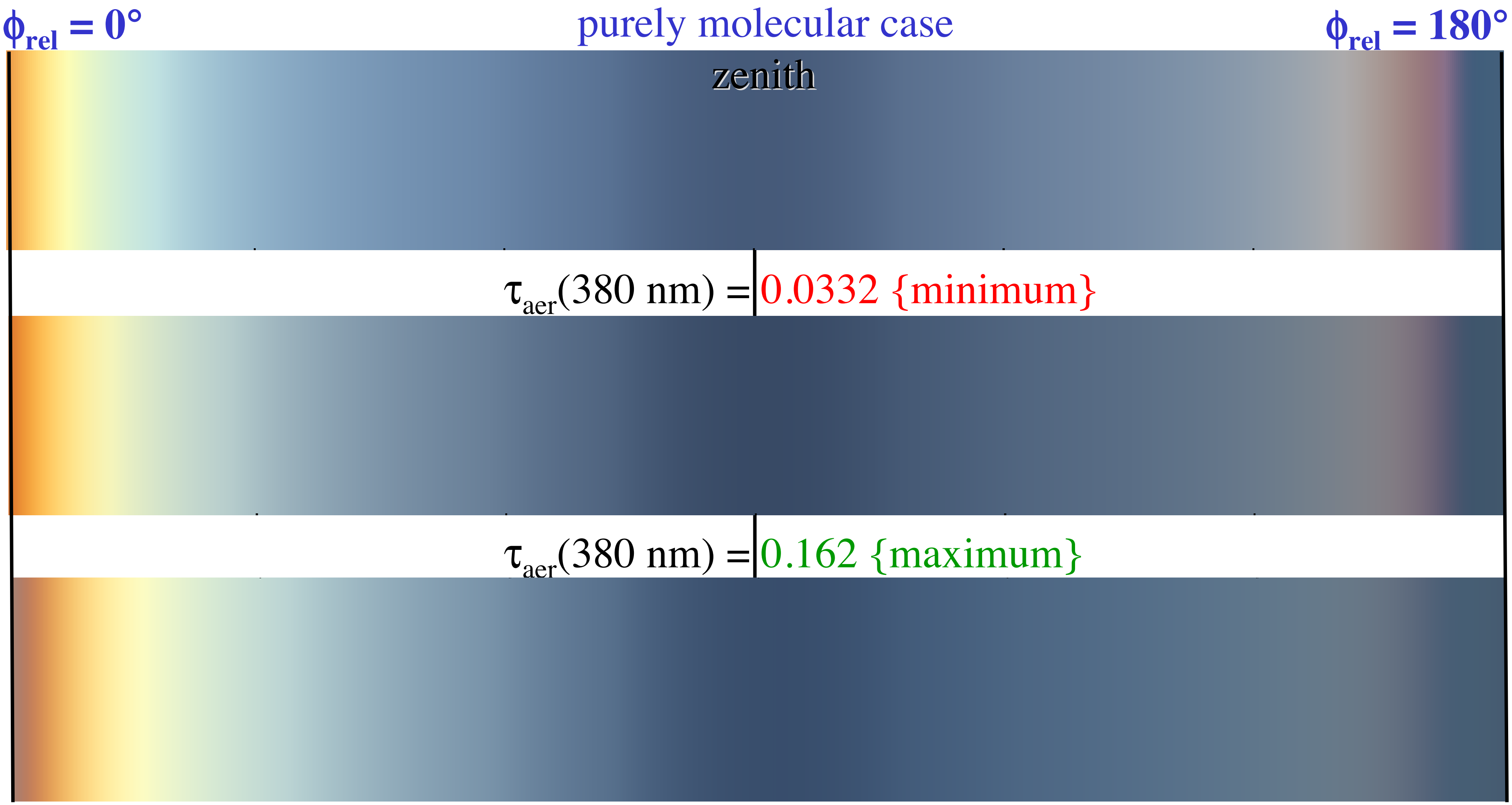
Corresponding u´,v´(ϕ_{rel},*h*) curves show why a purely molecular atmosphere can give both **(1)** redder ATA & **(2)** a less-red solar sky: a *little* aerosol scattering reddens the solar sky at the ATA's expense.



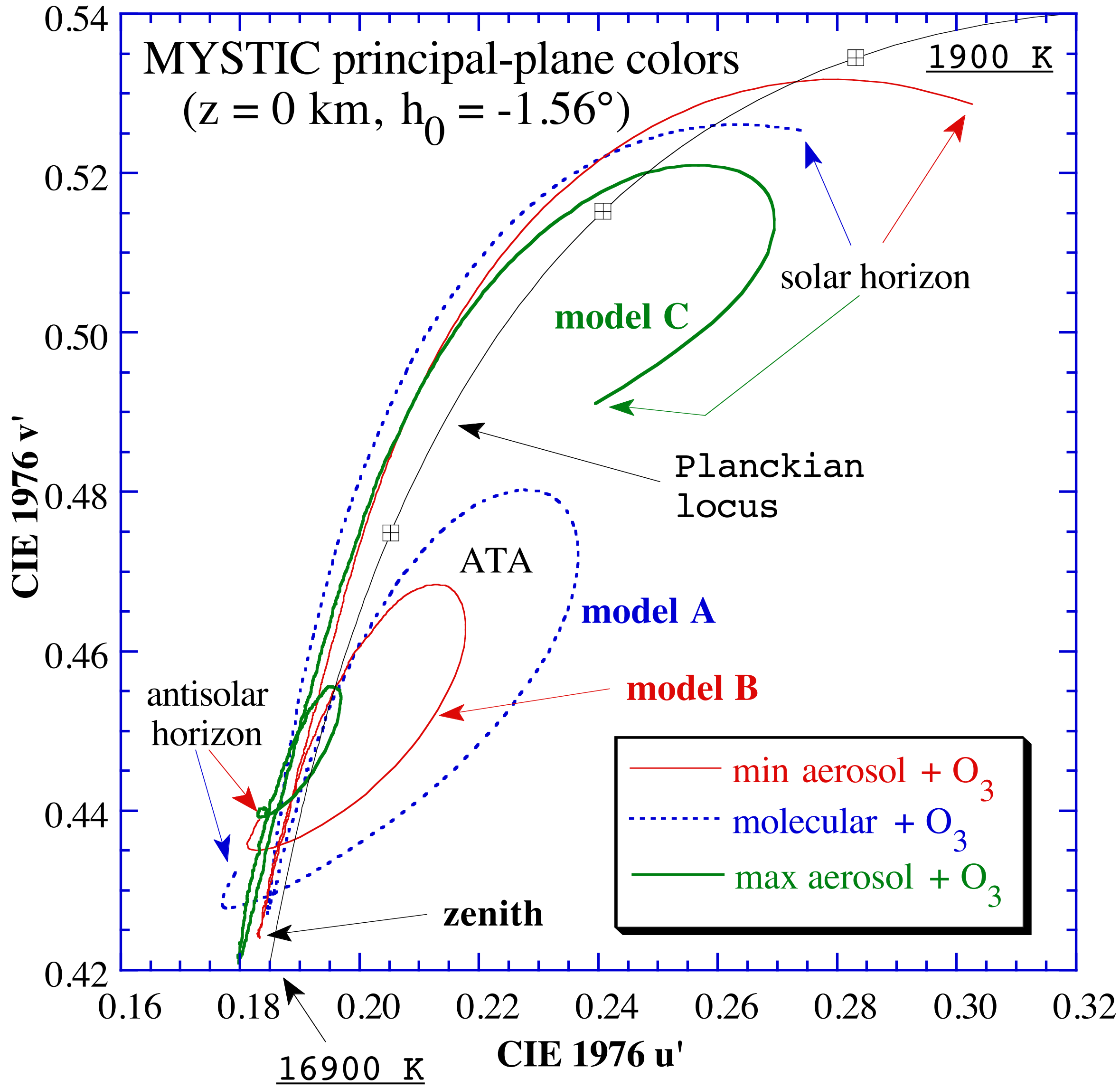


Then simulate twilight colors along clear-sky principal plane. The resulting MYSTIC meridional colors for high, low, & zero aerosol amounts make sense, but perhaps only in hindsight.

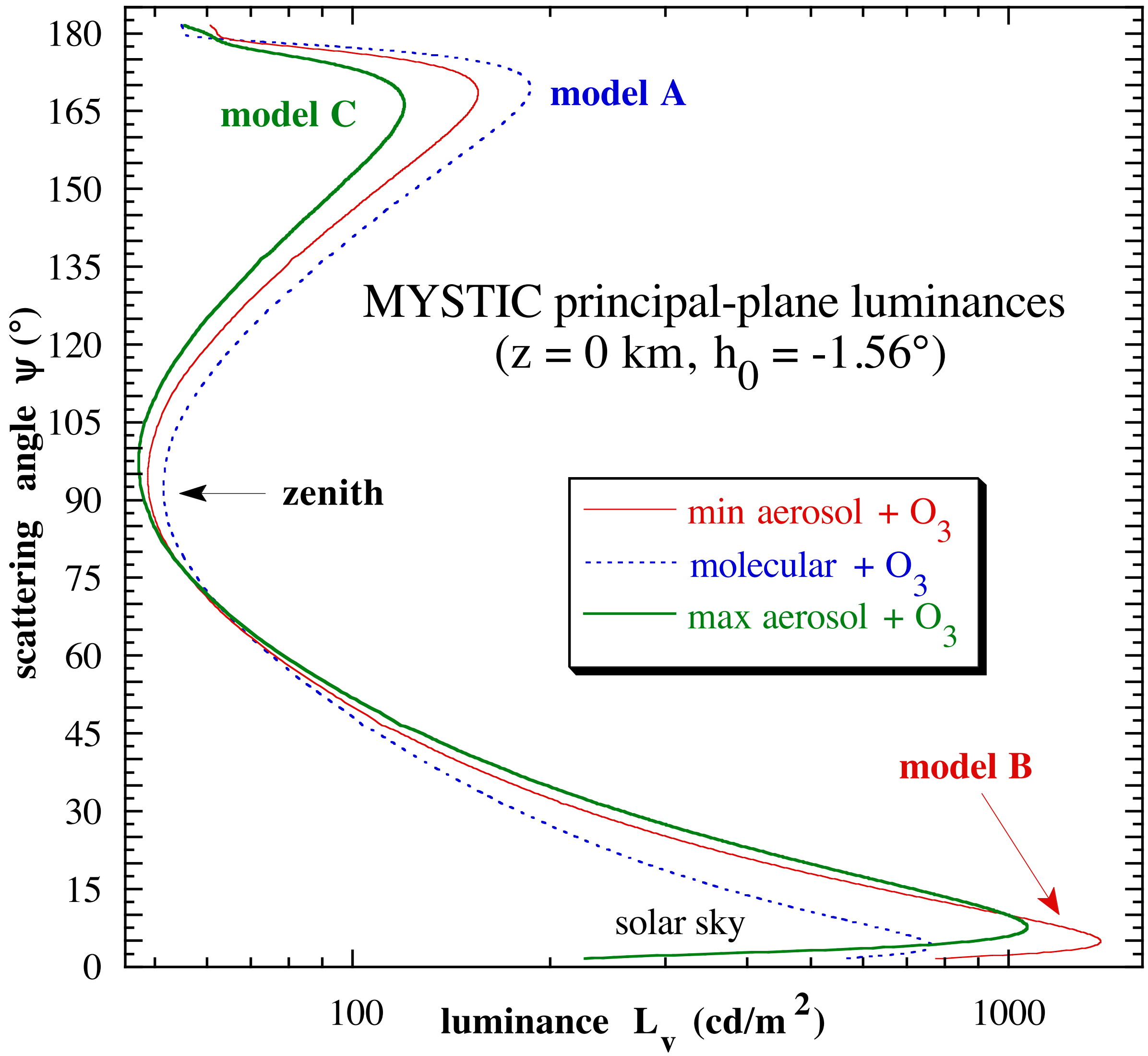
MYSTIC principal-plane colors
$h_0 = -1.56°, z = 0$ km



So while reddest ATA occurs in a molecular atmosphere, the reddest solar sky (*vs*. sun's disk) seems to require some unknown minimal τ_{aer}. Larger τ_{aer} amounts desaturate & make bluer *both* the ATA & solar sky.

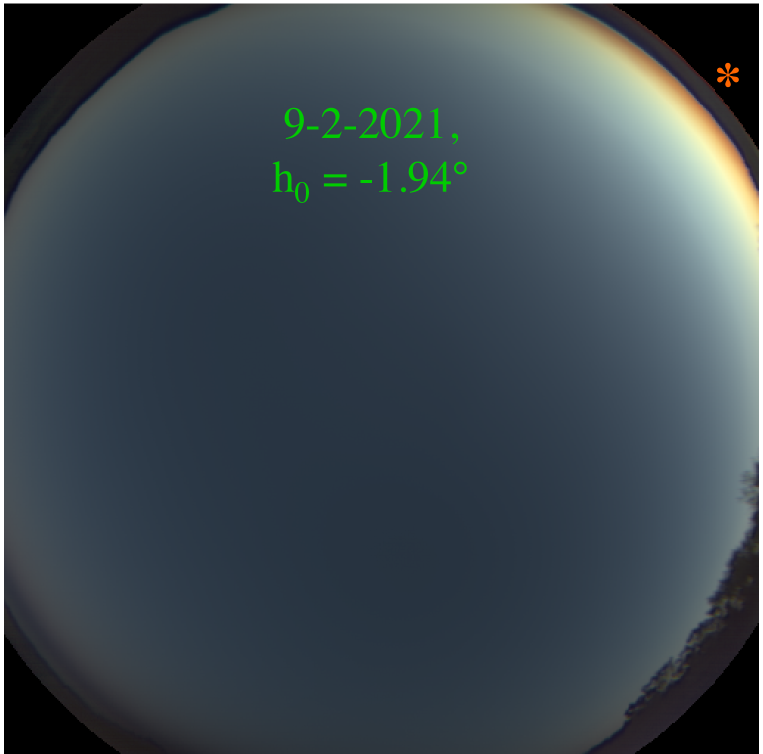


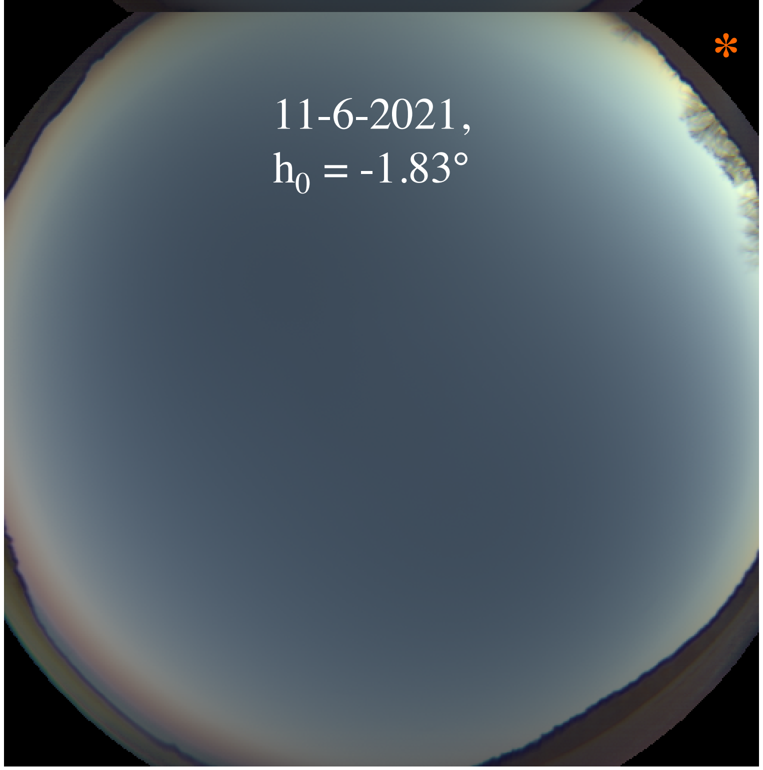
Much like twilight colors, MYSTIC twilight luminances L_v respond consistently to aerosols added to a molecular atmosphere: strong aerosol forward scattering ↑ solar-sky L_v but ↓ antisolar-sky L_v.

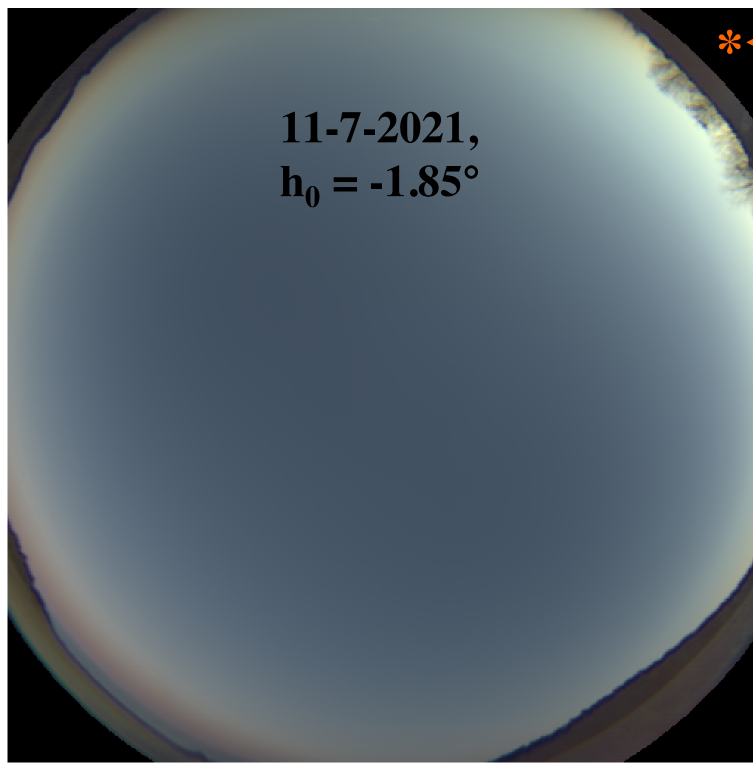


Finally, measure spectra & colors across the clear twilight sky & then analyze them as functions of date, ϕ_{rel}, & scattering angle Ψ at ~ same h_0.

All skies in this set are from a rural site near Marion Center, PA.





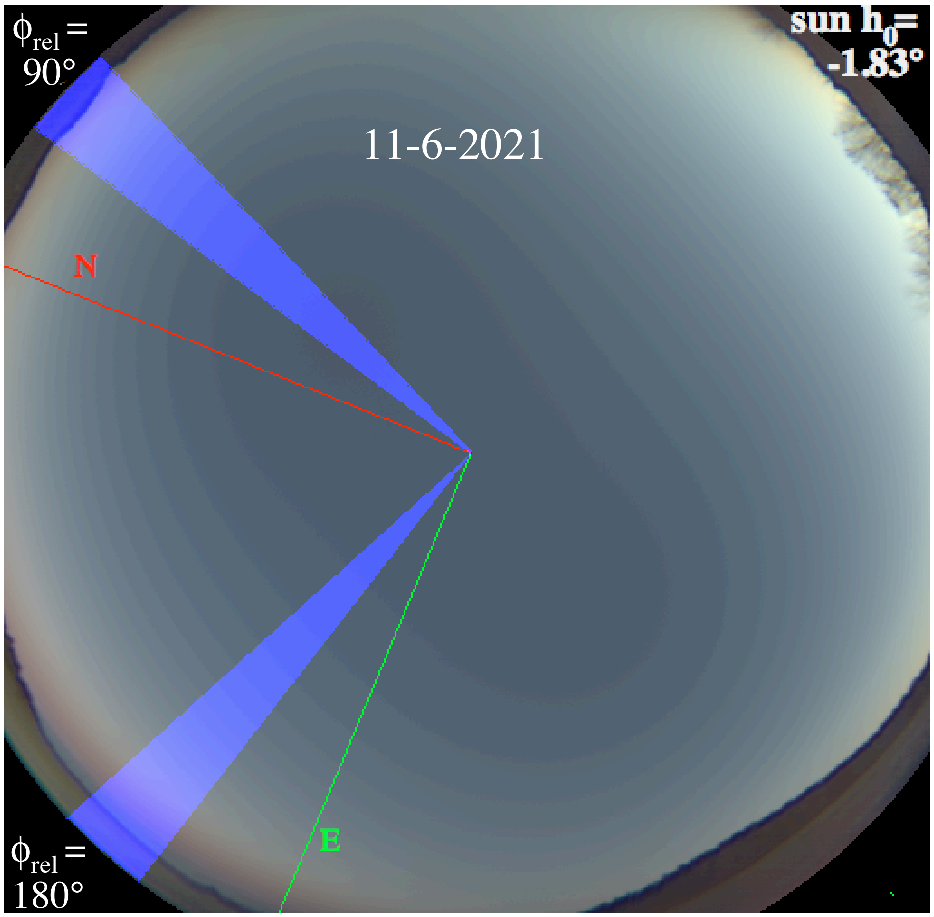


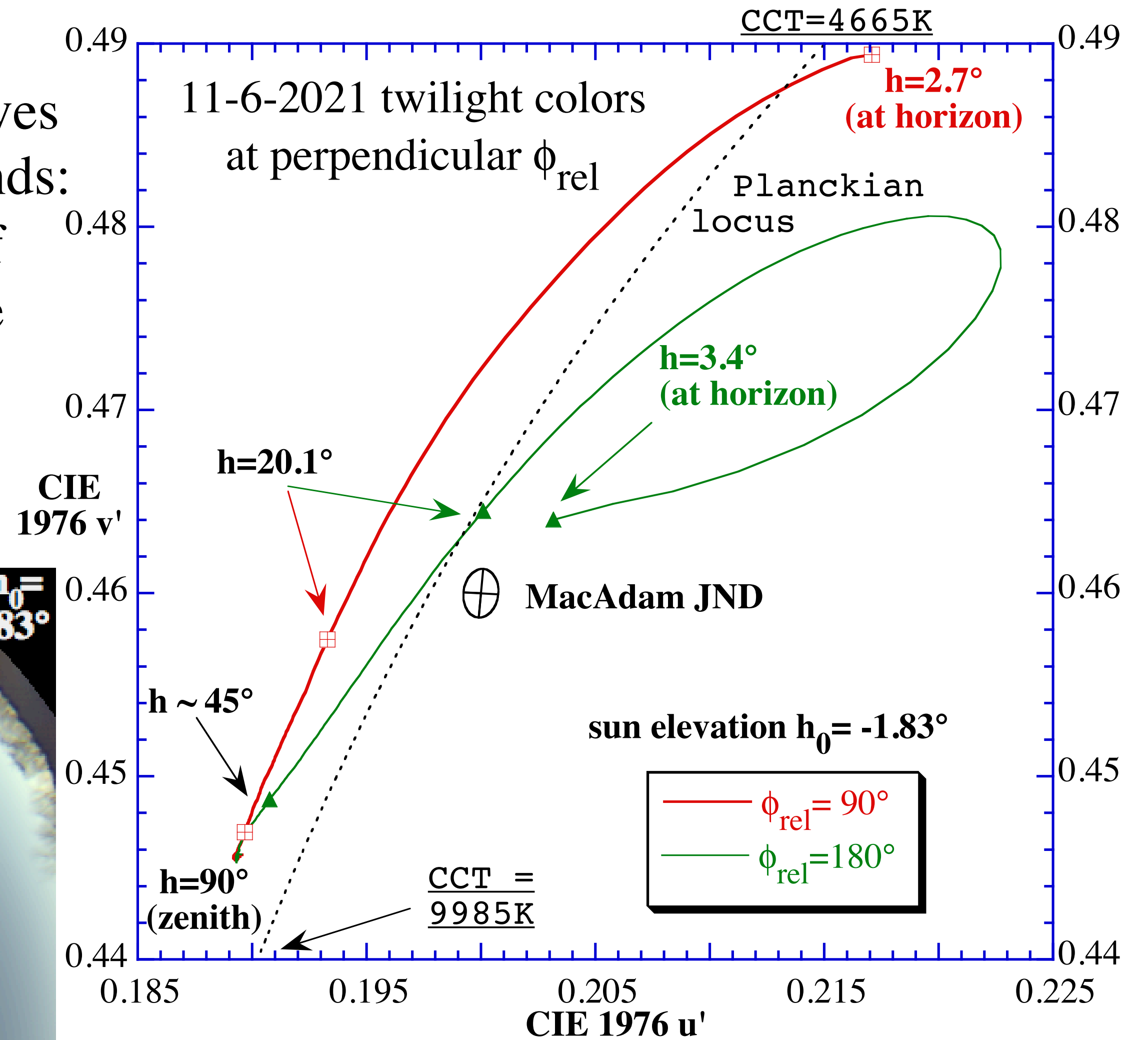
approximate sun position

To acquire such all-sky spectra, use another hyperspectral camera: a Specim IQ imaging spectrometer fitted with a Nikon FC-E8 fisheye.

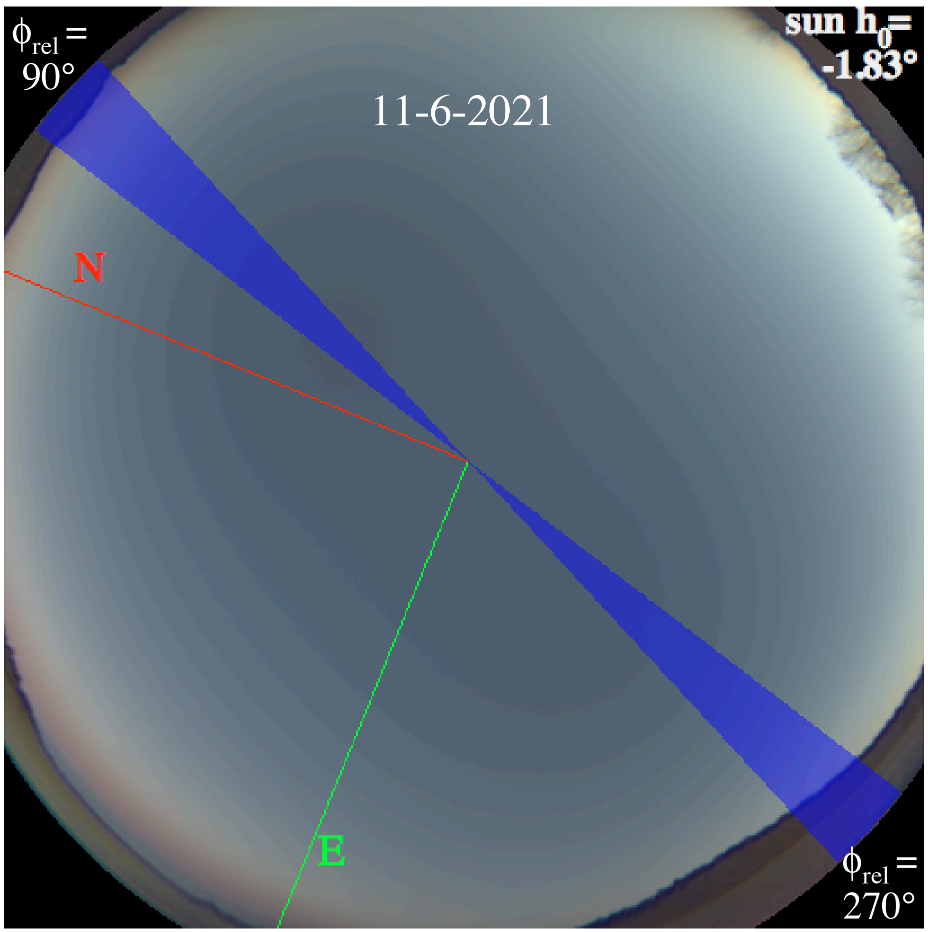
For typical clear-sky twilights, scan times range from 5 – 150 secs. This lens & camera combination does crop the circular image slightly, but careful camera orientation yields cardinal-direction ϕ_{rel} of 0° (solar azimuth), 90°, 180° (antisolar), & 270° in each scan.

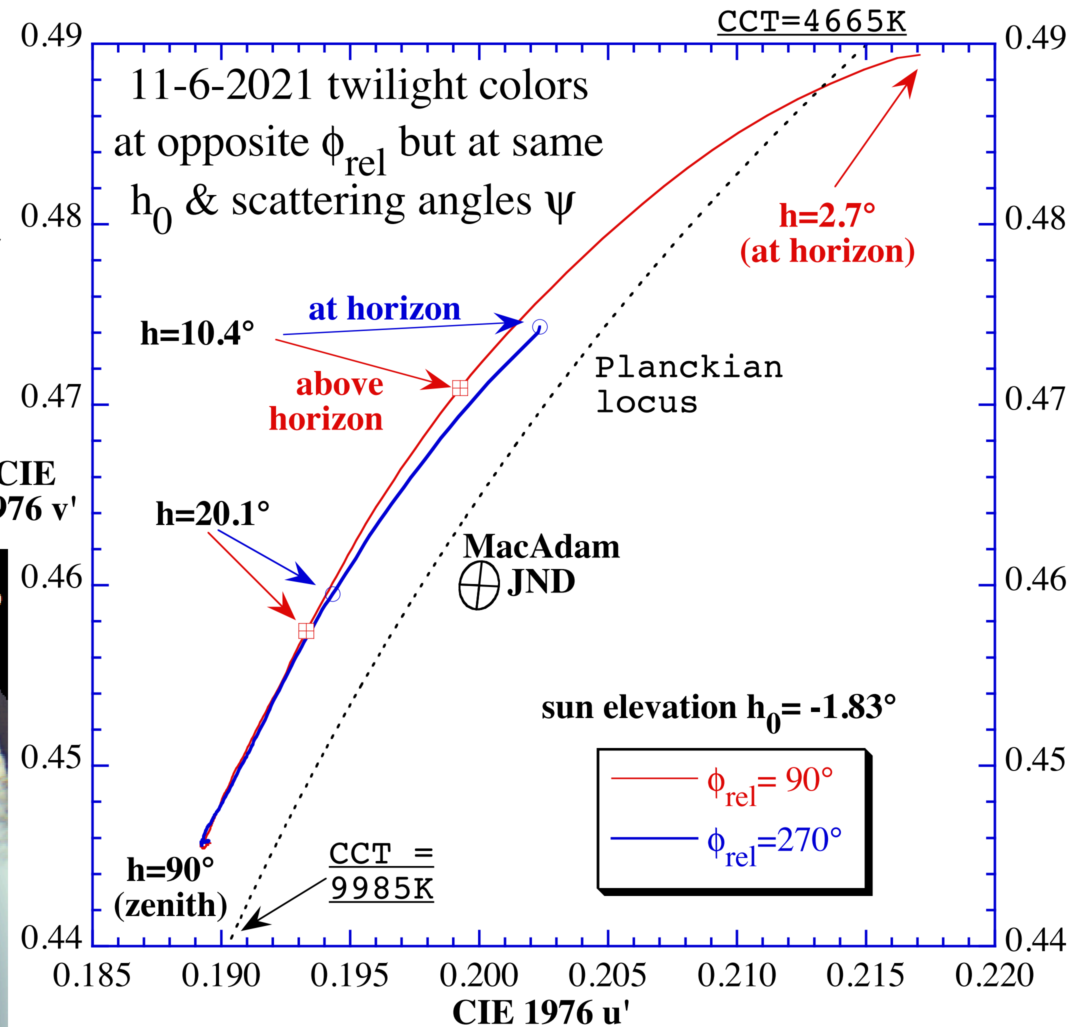
Averaging twilight colors in sectors centered on ϕ_{rel} = 90° & 180° ± 5° gives visibly different meridional color trends: although ϕ_{rel} = 90° crosses the Belt of Venus near the horizon (slide **31**), the *local maximum* in skylight redness seen at 180° is often absent at 90°.

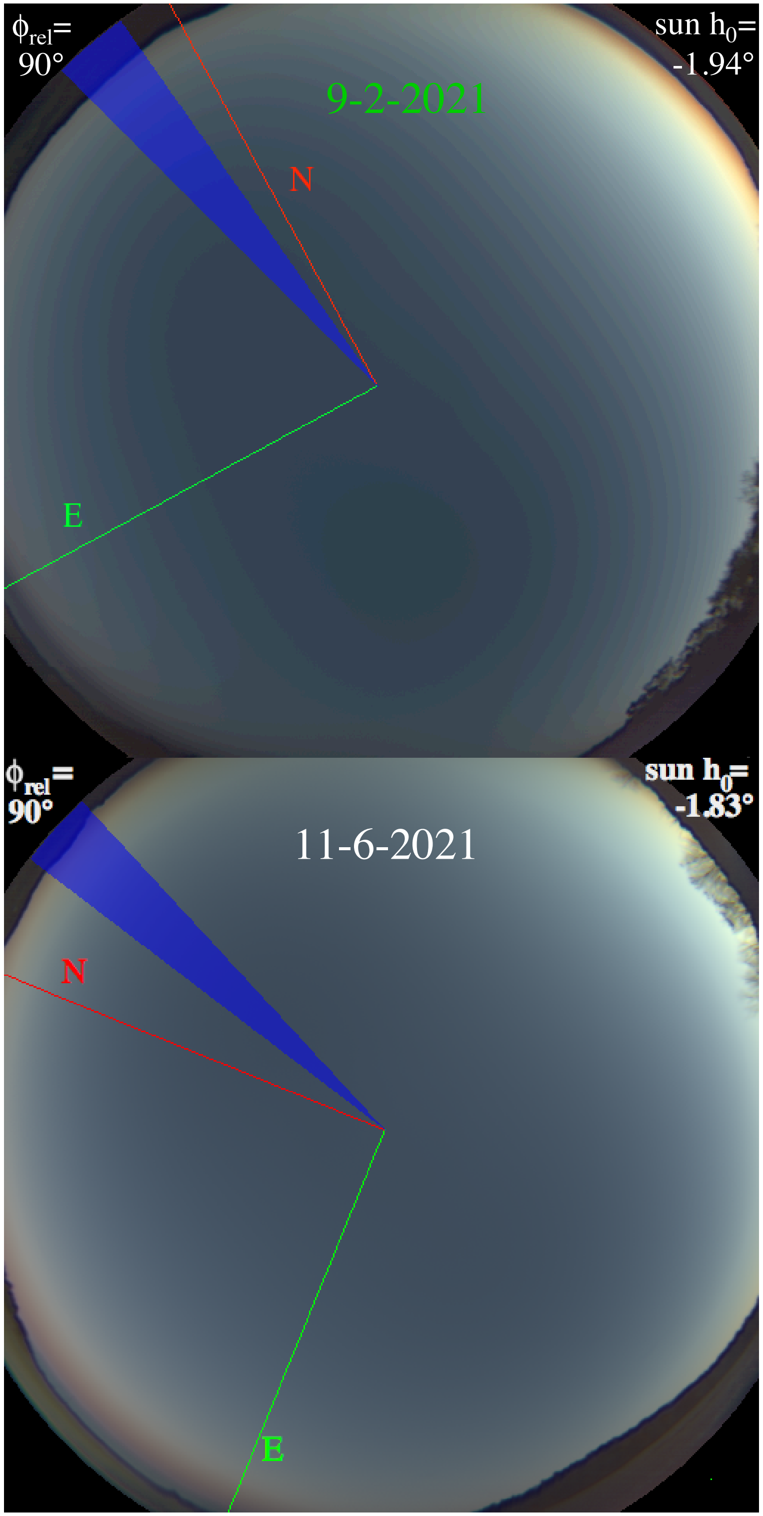


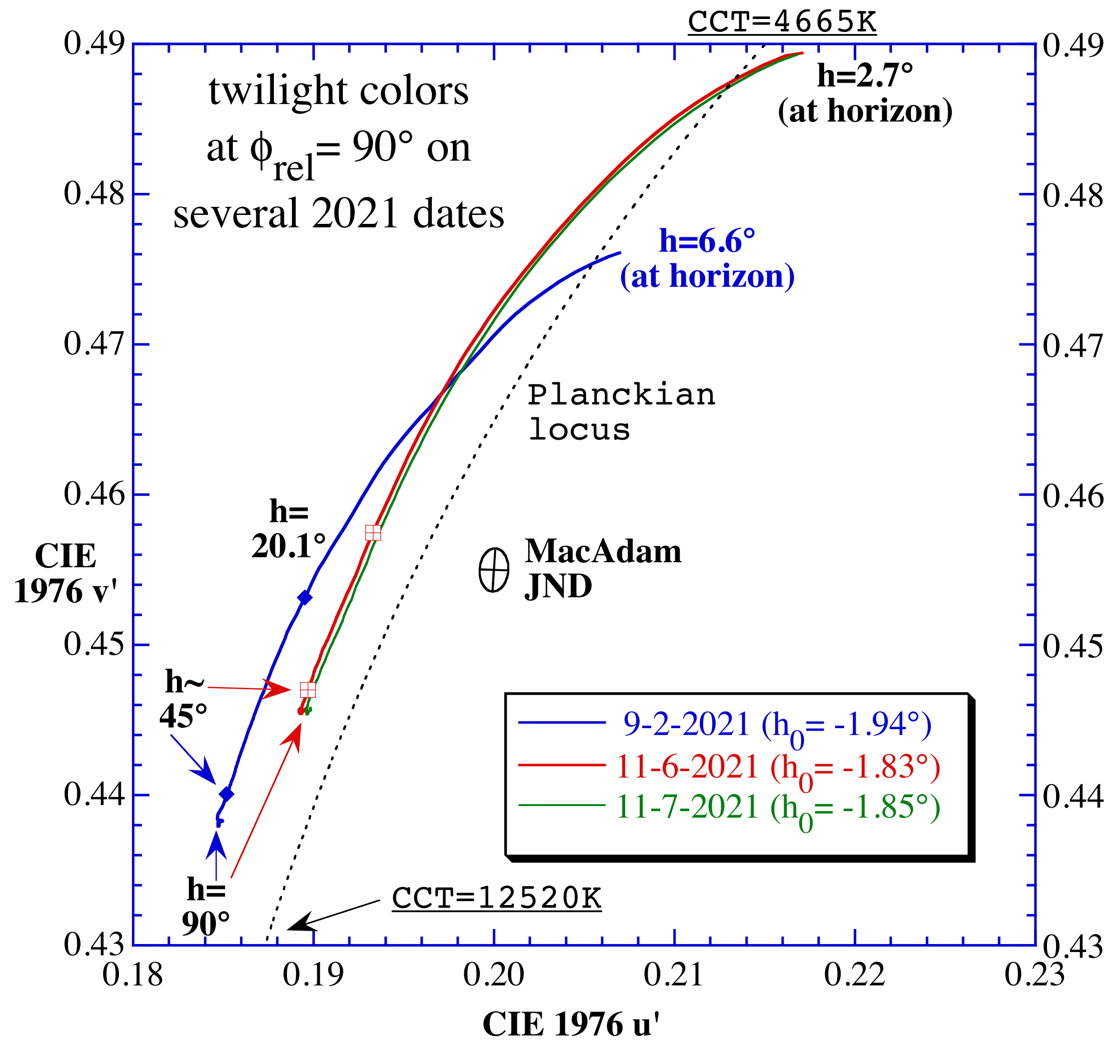


At the same Ψ (say, ϕ_{rel} = 90° & 270° for the same h & h_0), *in principle* simultaneously measured sky colors should be the same. Yet often they are not because your local troposphere's volume of ~ 10,000 km³ (within a 20 km radius) may well have perceptible spatial inhomogeneities in τ_{aer}.

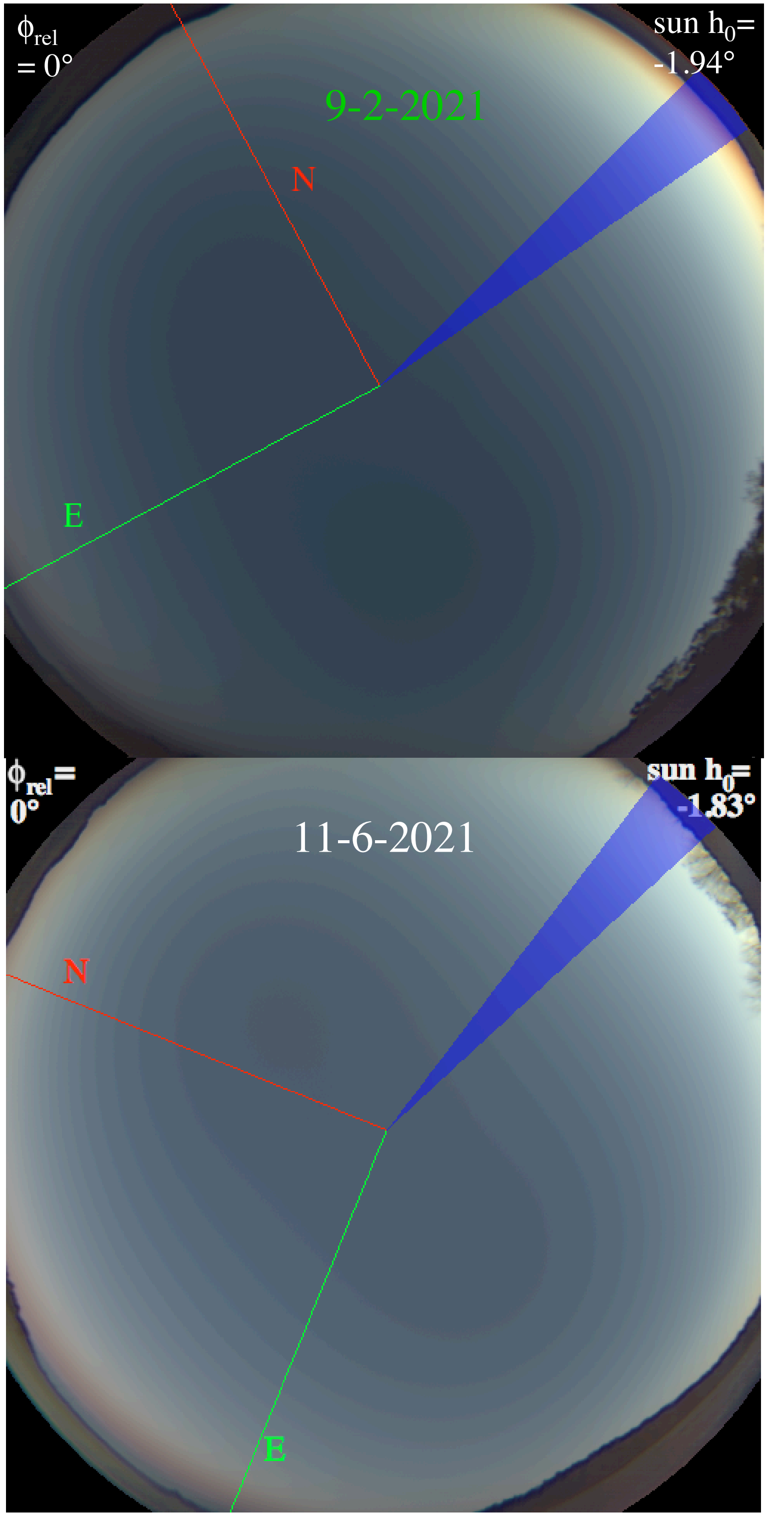


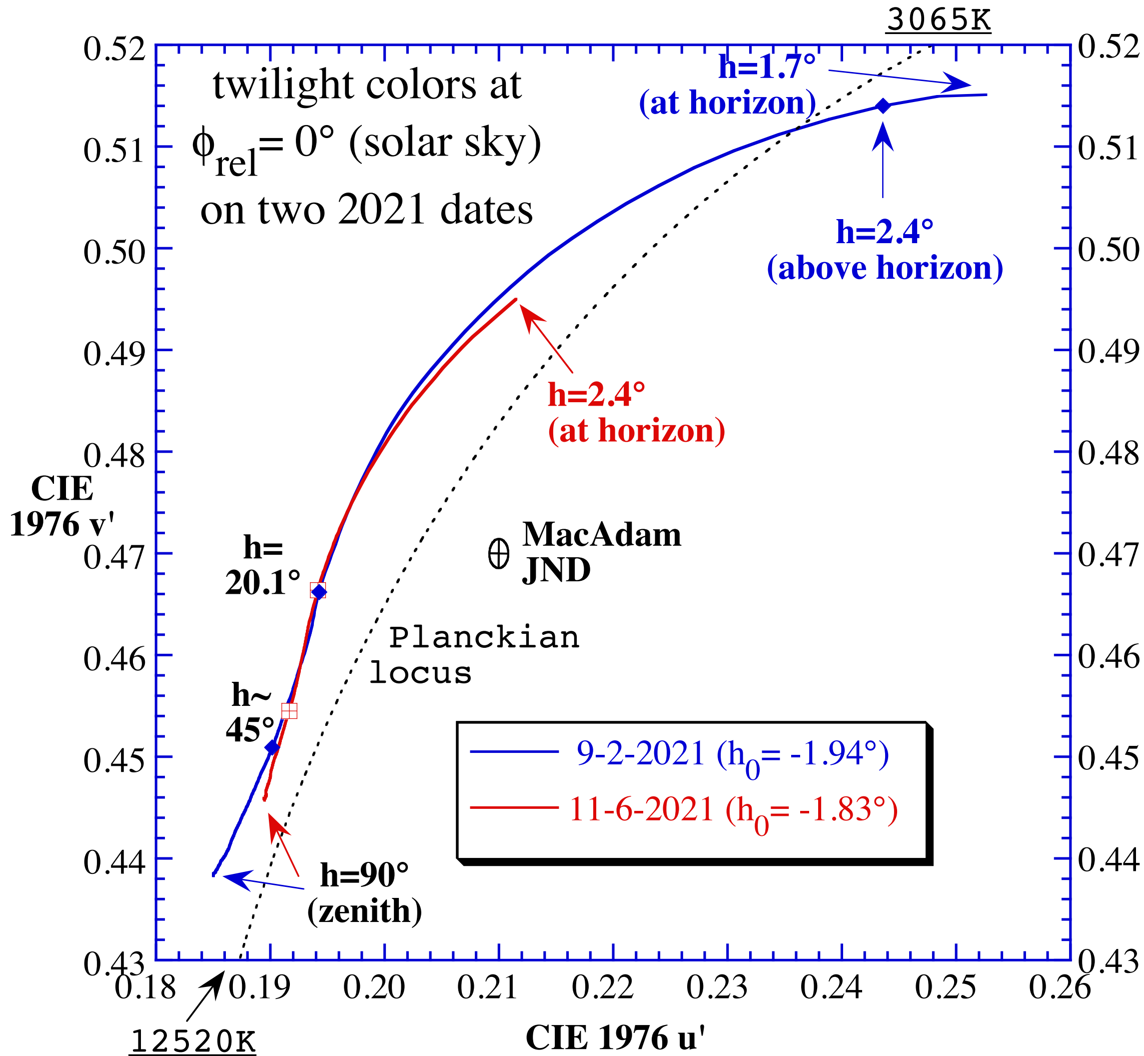






At ϕ_{rel} = 90°, 9-2-2021's turbid, higher ΔL_v sky is (1) bluer at the zenith & (2) bluer (*i.e.*, less red) at the horizon. In slide **26**, twilight spectra from the MD coastal site exhibit large shifts in antisolar color distributions as τ_{aer} ↑. Do similar color shifts occur in this inland site's solar sky?





Yes, but for this site's solar sky ($\phi_{rel} = 0°$), increases in τ_{aer} make (1) the horizon sky *redder* & (2) the zenith sky bluer, as seen both in the photos & CIE diagram. This is basic radiative-transfer accounting: making the horizon sky redder & relatively brighter makes the zenith sky bluer & darker.

Conclusions – haze & daytime clear-sky colors

1) Although scattering by tropospheric haze "merely" desaturates clear-sky colors, we haven't known the details until now:

(a) some hazy-sky u´,v´(*h*) curves are shifted toward Planckian locus while others are shifted along it to lower CCTs,

(b) this colorimetric shift's size doesn't depend solely on τ_{aer},

(c) at higher *h*, hazy antisolar skylight is *relatively* more bluish than light from the same sky at ϕ_{rel} = 90° & 270°,

(d) even as haze decreases skylight's overall color gamut & ΔL_v range.

2) At our measurement sites, TF_λ consistently exhibits:

(a) haze-induced bluish biases near the horizon (perhaps from aerosol multiple scattering over large slant-path τ_{aer}),

(b) reddening with broad local maxima from ~ 680-730 nm at most *h*, &

(c) very few local minima (*i.e.*, aerosol absorption) from 400-700 nm.

3) A 2nd-order scattering model shows skylight's high-*h* hooks are caused by **(a)** aerosol scattering that reddens *slightly* as our gaze nears the sun, plus **(b)** reduced multiple scattering at higher *h* that makes skylight bluer.

Conclusions – haze & twilight clear-sky colors

1) Both modeling & measurements of antisolar twilight sky suggest that adding *any* amount of typical tropospheric aerosols to a molecular atmosphere → an ATA that **(a)** is less red & **(b)** has a smaller color gamut.

2) However, *small* amounts of such aerosols will redden the near-horizon solar sky → larger gamuts for **(a)** azimuthal & **(b)** principal-plane colors.

3) So in radiative-transfer accounting terms, a *little* aerosol scattering reddens the solar sky at the ATA's expense.

4) Adding more aerosol than some unknown minimum amount will desaturate & make bluer *both* the ATA & the solar sky.

5) We come closest to seeing the molecular ATA/dark segment pair's vivid colors at high z, such as from a mountaintop or aircraft.

6) Modeled twilight luminance $L_v(\Psi)$ responds plausibly to minimal added aerosols: their strong forward scattering increases solar-sky L_v but decreases antisolar-sky L_v. However, adding many more aerosols reduces L_v local maxima on both sides of the clear twilight sky.


And what color is the clear nighttime sky?
Blue, of course — but only if you're *very* patient.
That's my quiz question for you — now I'm glad take yours.