Advances in Measuring Solar Reflectance—or,

Why that roof isn't as cool as you thought it was.

Ronnen Levinson, Ph.D.

Scientist
Heat Island Group
Lawrence Berkeley National Laboratory

Environmental Energy Technologies Division Seminar
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RMLevinson@LBL.gov
tel. (510) 486-7494

1. Prologue

Cool roof technologies

Old

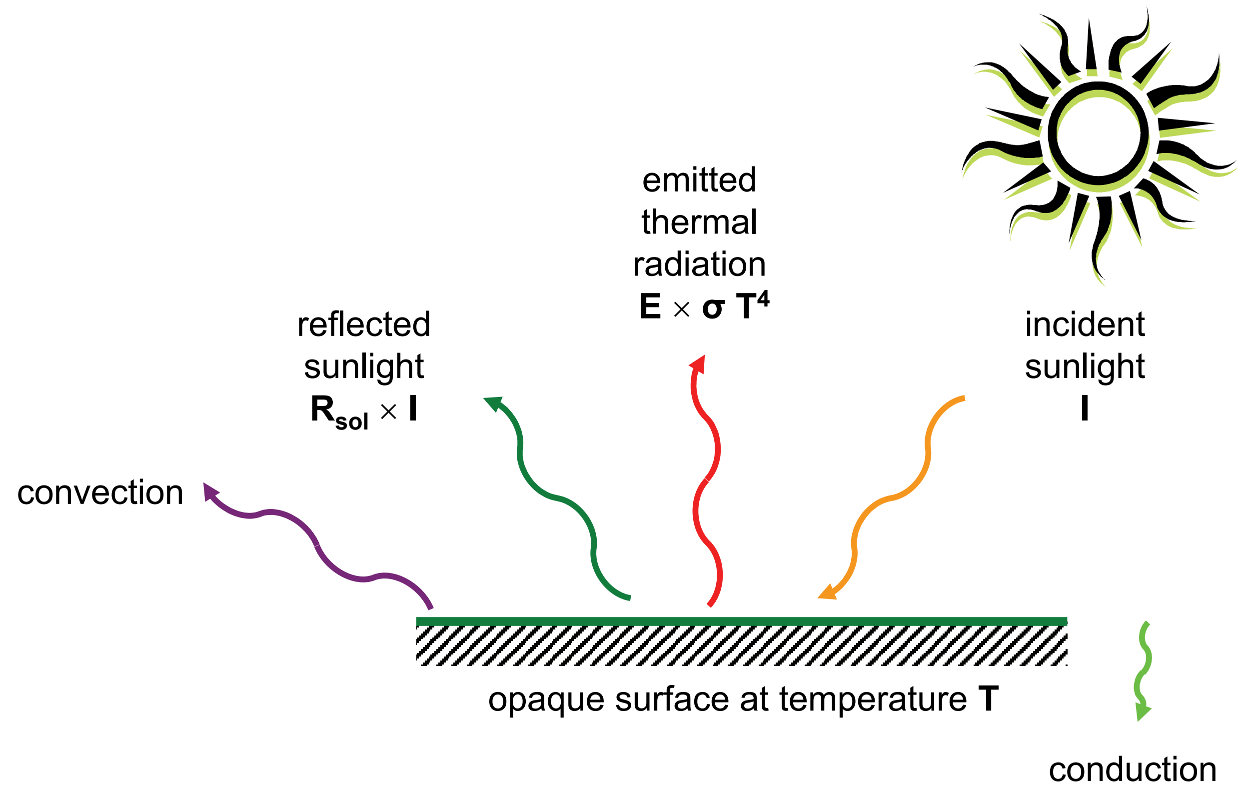
flat, white

pitched, white

New

pitched, cool & colored

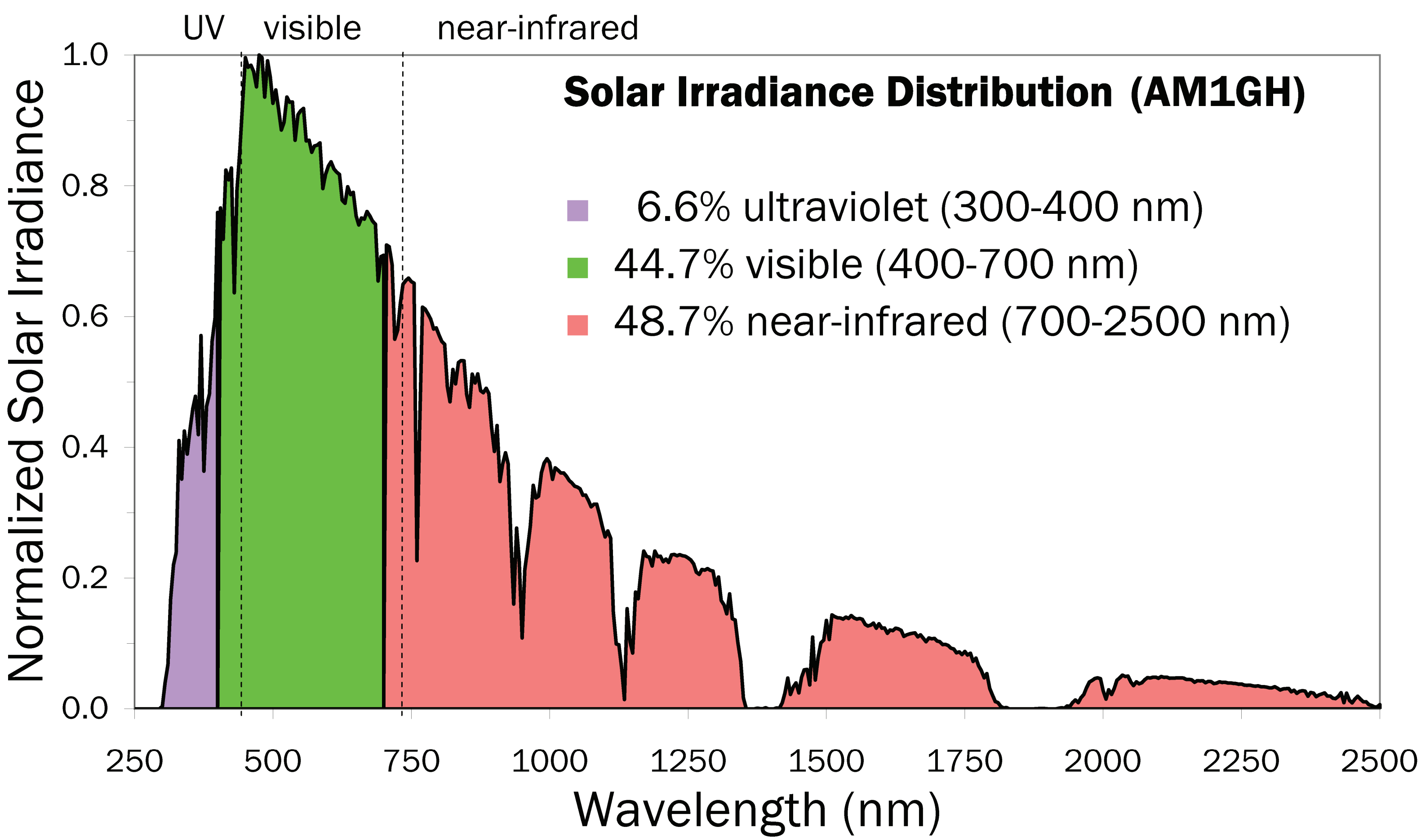
What makes a surface cool?



- **High solar reflectance** (R_{sol}) lowers solar heat gain (0.3 - 2.5 μm)
- **High thermal emittance** (E) enhances thermal radiative cooling (4 - 80 μm)

high solar reflectance + high thermal emittance = **low surface temperature**

More than meets the eye



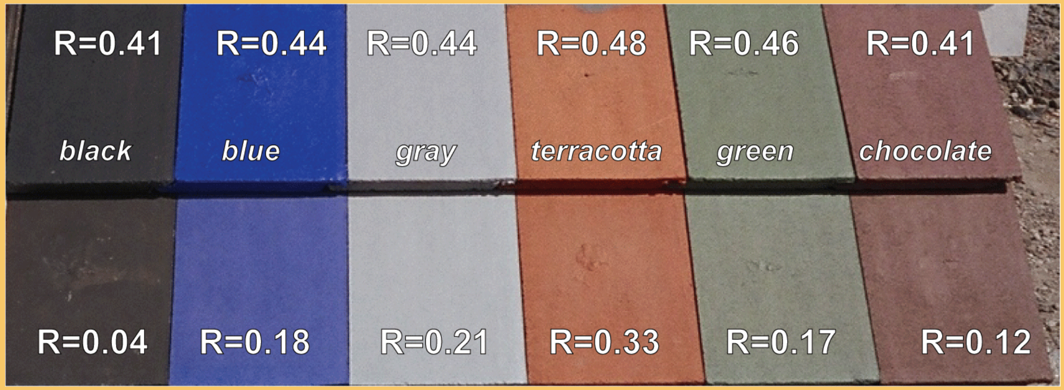
AM1GH = (clear sky) air mass 1 global horizontal

Solar reflectance $\mathbf{R}_{\mathbf{sol}}$ = 6.6% × ultraviolet reflectance $\mathbf{R}_{\mathbf{uv}}$ +
44.7% × visible reflectance $\mathbf{R}_{\mathbf{vis}}$ +
48.7% × near-infrared reflectance $\mathbf{R}_{\mathbf{nir}}$

Cool colored roofing

cool concrete tile
R ≥0.40

standard concrete tile
(same color)

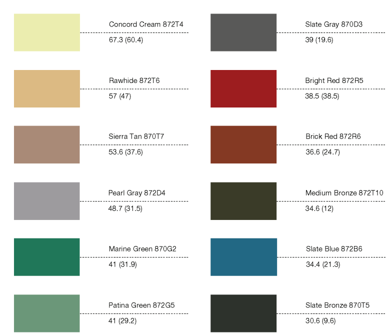


Courtesy
American
Rooftile
Coatings

	black	blue	gray	terracotta	green	chocolate
cool concrete tile	R=0.41	R=0.44	R=0.44	R=0.48	R=0.46	R=0.41
standard concrete tile	R=0.04	R=0.18	R=0.21	R=0.33	R=0.17	R=0.12
solar reflectance gain =	**+0.37**	**+0.26**	**+0.23**	**+0.15**	**+0.29**	**+0.29**

cool clay tile
R ≥0.40

Courtesy
MCA Clay Tile



cool metal
R ≥0.30

Courtesy
BASF Industrial
Coatings

cool fiberglass asphalt shingle
R ≥0.25
Courtesy
Elk Corporation

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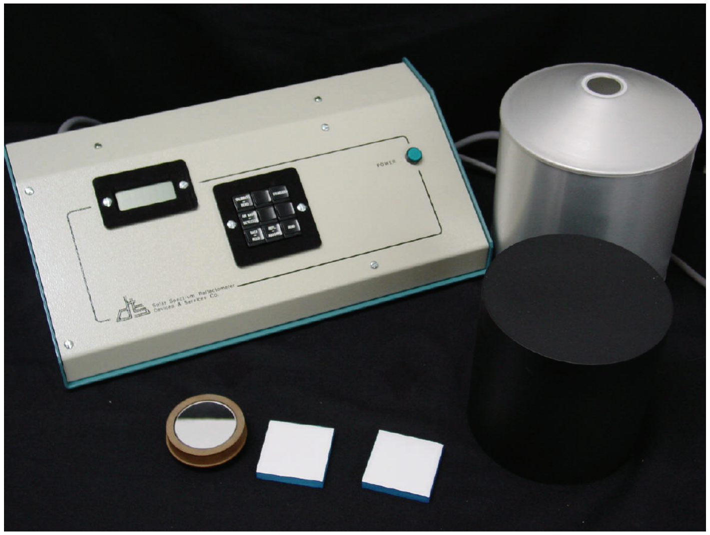
2. Down the rabbit hole

Reflectance measurement instruments



Solar Spectrum Reflectometer (ASTM C1549)

Solar spectrophotometer (ASTM E903)

Pyranometer (ASTM E1918, LBNL E1918A)

Early adventures, circa 2001

- Method A: R_{sol} measured with solar spectrum reflectometer (ASTM C1549)
- Method B: R_{sol} measured with solar spectrophotometer (my variant on ASTM E903)
- **ΔR_{sol} = A – B small for most “standard” colors, large for many “cool” colors**

“standard” colors

A	0.089	0.045	0.162	0.120	0.241	0.215	0.114
B	0.083	0.045	0.168	0.119	0.234	0.195	0.114
Δ	**0.006**	**0.000**	**-0.006**	**0.001**	**0.007**	**0.020**	**0.000**

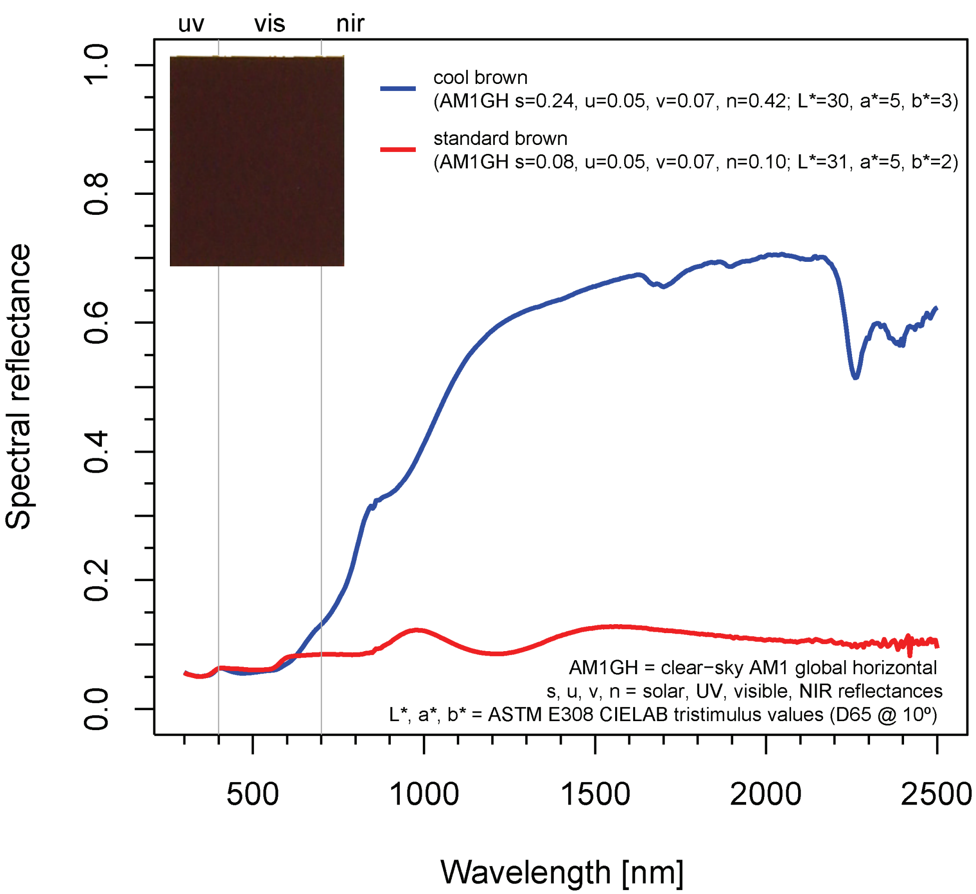
“cool” colors

A	0.292	0.255	0.262	0.249	0.391	0.333	0.318
B	0.241	0.204	0.272	0.236	0.357	0.282	0.269
Δ	**0.051**	**0.051**	**-0.010**	**0.013**	**0.034**	**0.051**	**0.049**

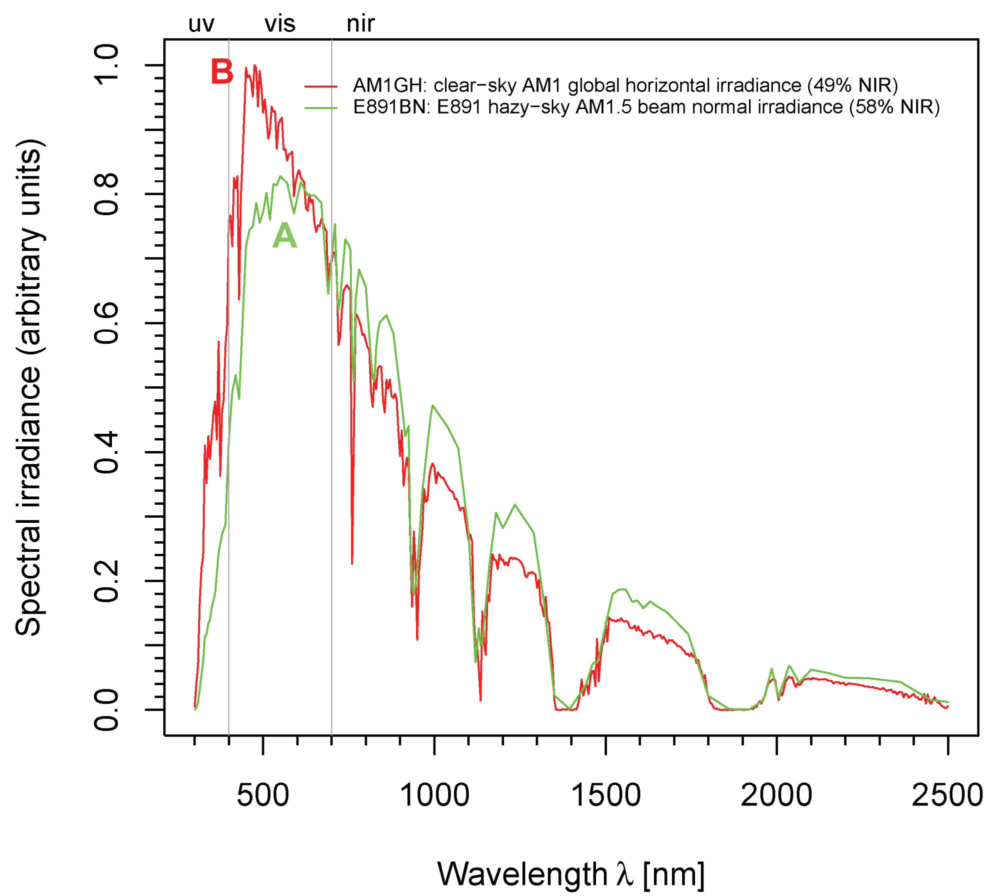
Why? Two different spectral irradiances

$$R_{\mathrm{sol}} = \frac{\int_{\mathcal{S}} i(\lambda)\, r(\lambda)\, d\lambda}{\int_{\mathcal{S}} i(\lambda)\, d\lambda}$$

cool colors reflect selectively



methods A, B assume different i(λ)



3. All about E891BN

ASTM standards E891, E903, C1549 (i)

- ASTM E891-87(1992) (withdrawn 1999)
  - *Tables for Terrestrial Direct Normal Solar Spectral Irradiance for Air Mass 1.5*
  - AM1.5 beam normal (BN, a.k.a. “direct normal”) solar spectral irradiance under hazy sky, $i_{E891BN}(\lambda)$
  - Succeeded by ASTM G159, G173, G197
- ASTM E903-96 (withdrawn 2005)
  - *Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres*
  - weights near normal-hemispherical solar spectral reflectance $r_{b,n}(\lambda)$ with $i_{E891BN}(\lambda)$ to calculate solar reflectance R_{E891BN}

$$R_{\mathrm{E891BN}} \equiv I_{\mathrm{E891BN}}^{-1} \int_{\mathcal{S}} i_{\mathrm{E891BN}}(\lambda)\, r_{\mathrm{b,n}}(\lambda)\, d\lambda$$

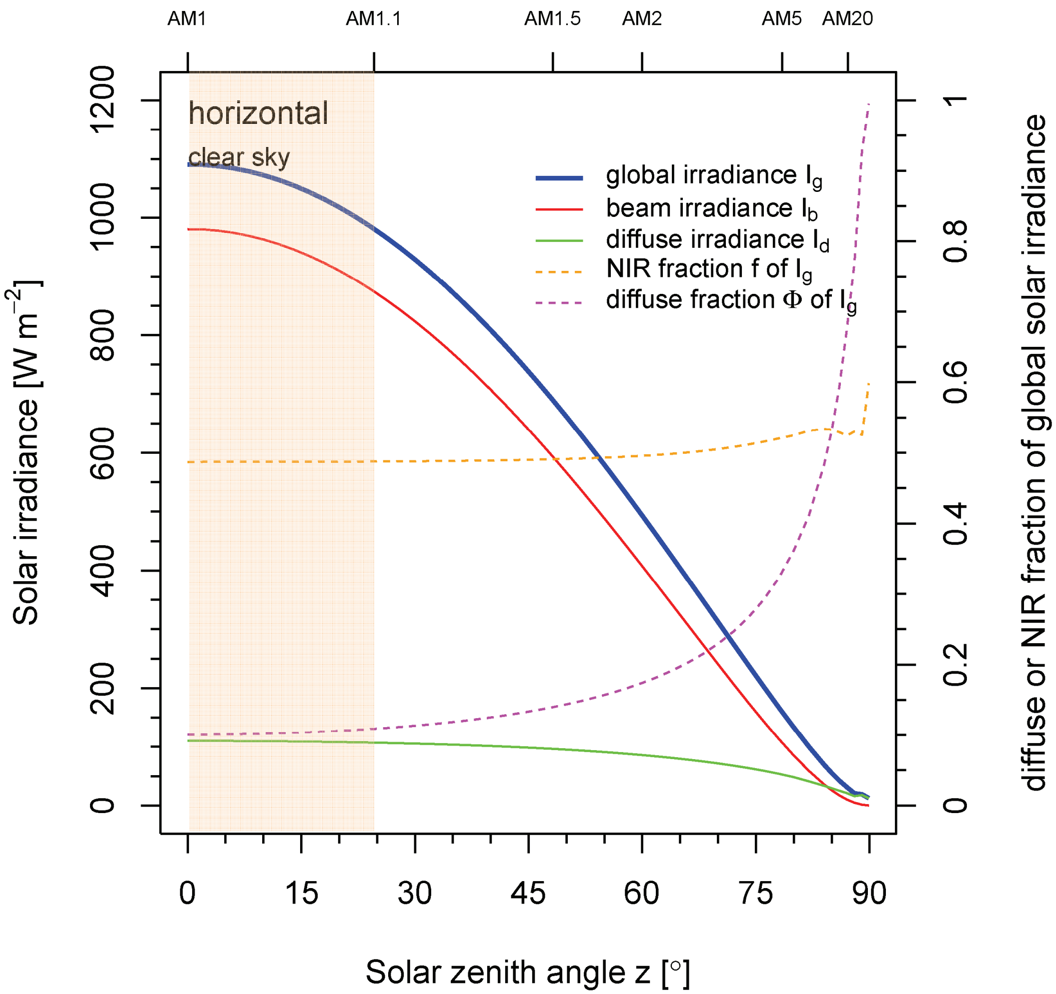
$$I_{\mathrm{E891BN}} \equiv \int_{\mathcal{S}} i_{\mathrm{E891BN}}(\lambda)\, d\lambda$$

ASTM standards E891, E903, C1549 (ii)

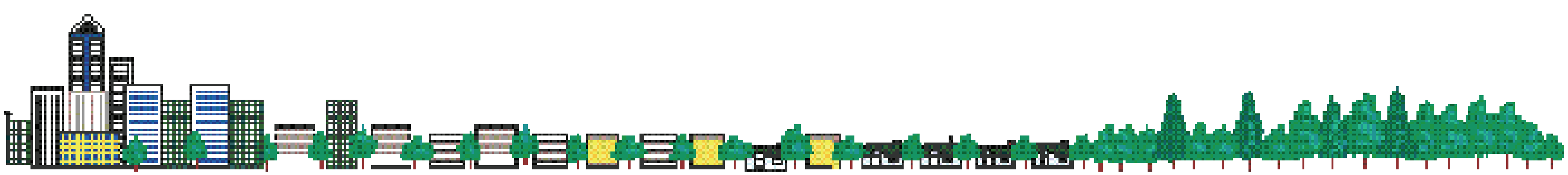
- ASTM C1549-04
  - *Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer*
  - measures diffuse-near normal solar reflectance (= near normal-hemispherical solar reflectance) with Devices & Services Solar Spectrum Reflectometer (SSR)
  - AM1.5 output of SSRv5 designed to emulate R_{E891BN}

- ASTM E903, C1549 measurements of R_{E891BN} used to rate solar reflectances of roofs, pavements
  - Cool Roof Rating Council (CRRC)
  - US EPA Energy Star
  - US Green Building Council LEED
  - ASHRAE 90.1
  - California Title 24 (via CRRC)
- ASTM E1918 (pyranometer) solar reflectance measurements also used

Applicability of $i_{E891BN}(\lambda)$, R_{E891BN}

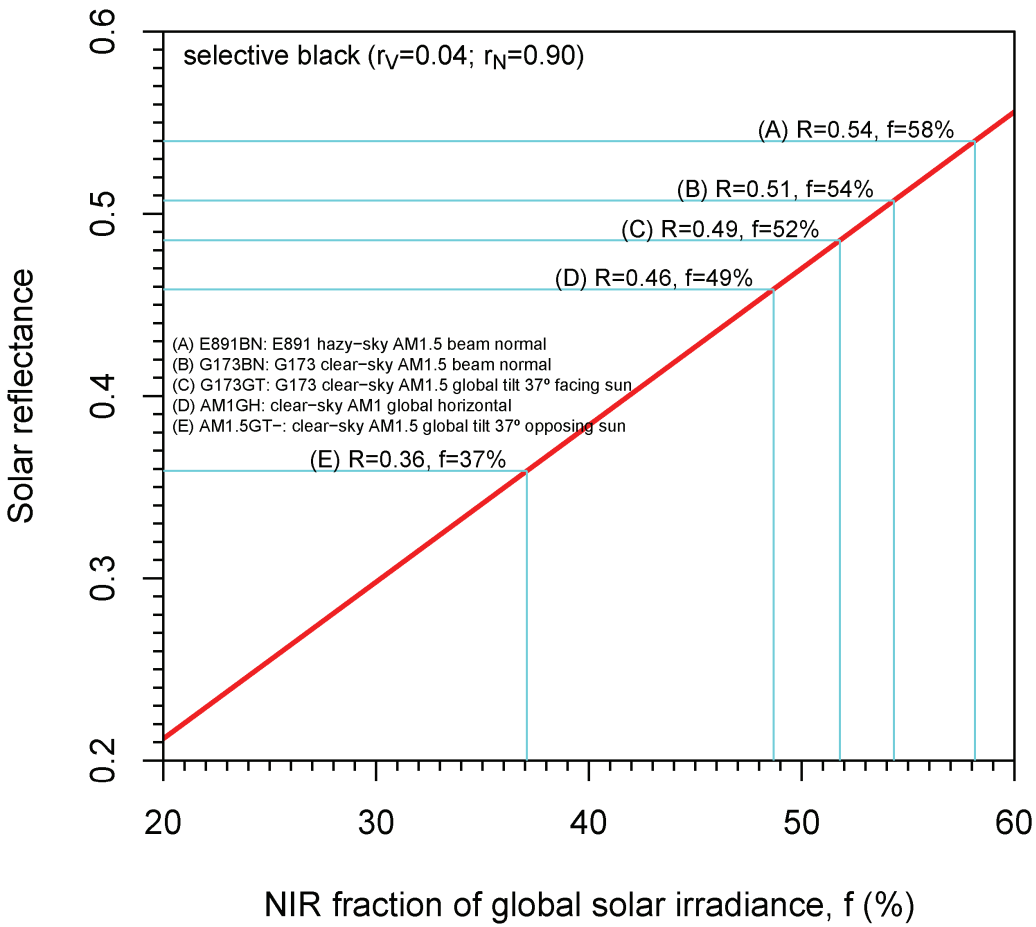


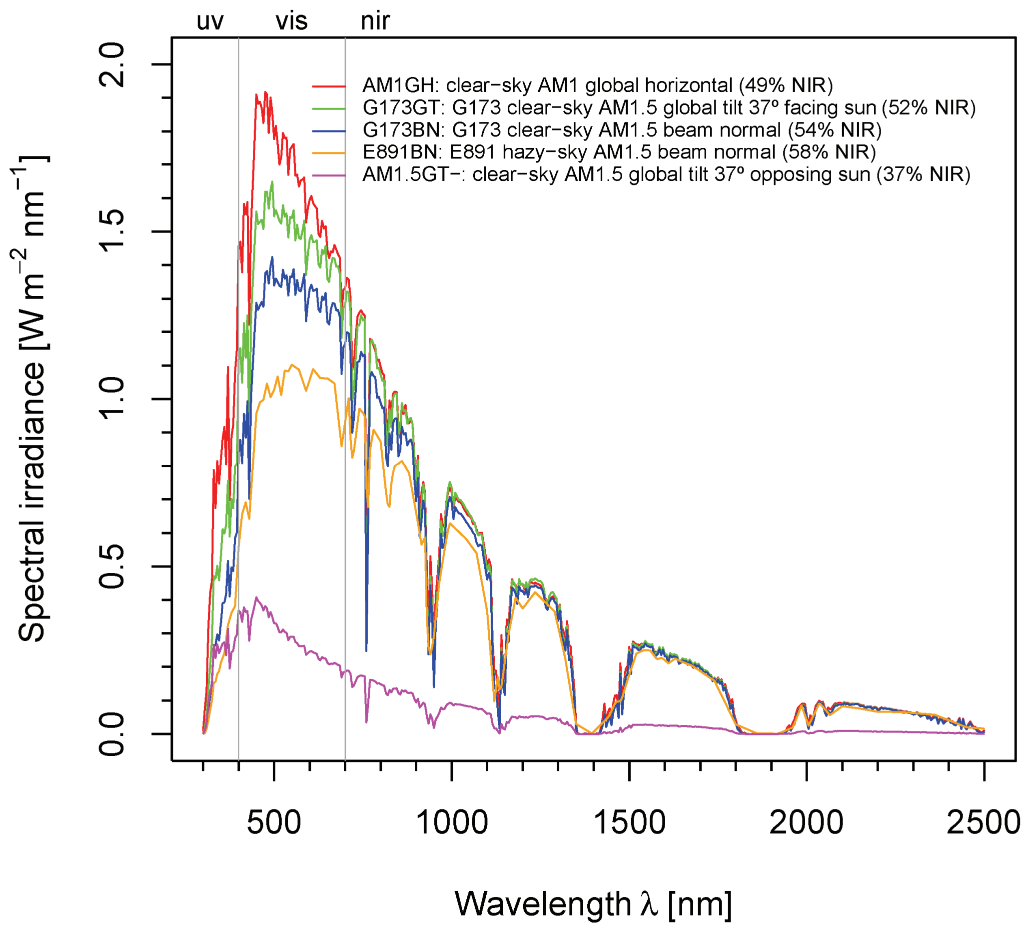
- global (a.k.a. hemispherical) =
  beam + diffuse
- beam (a.k.a. direct) sunlight =
  parallel rays from sun
- diffuse sunlight =
  light scattered from solar beam
  by atmosphere
- diffuse light "bluer" than direct light
  - lower NIR fraction
- concentrated sunlight nearly all direct
  - 10 suns ~ 1% diffuse
  - 100 suns ~ 0.1% diffuse
  - $i_{E891BN}(\lambda)$, R_{E891BN} OK
    for solar concentator (under hazy sky)
- global horizontal sunlight ~ 10% diffuse
  - $i_{E891BN}(\lambda)$, R_{E891BN} not OK
    for roofs, pavements



Effect of solar spectral irradiance on R_{sol}

R_{E891BN} can overestimate solar reflectance of selective black by 0.08





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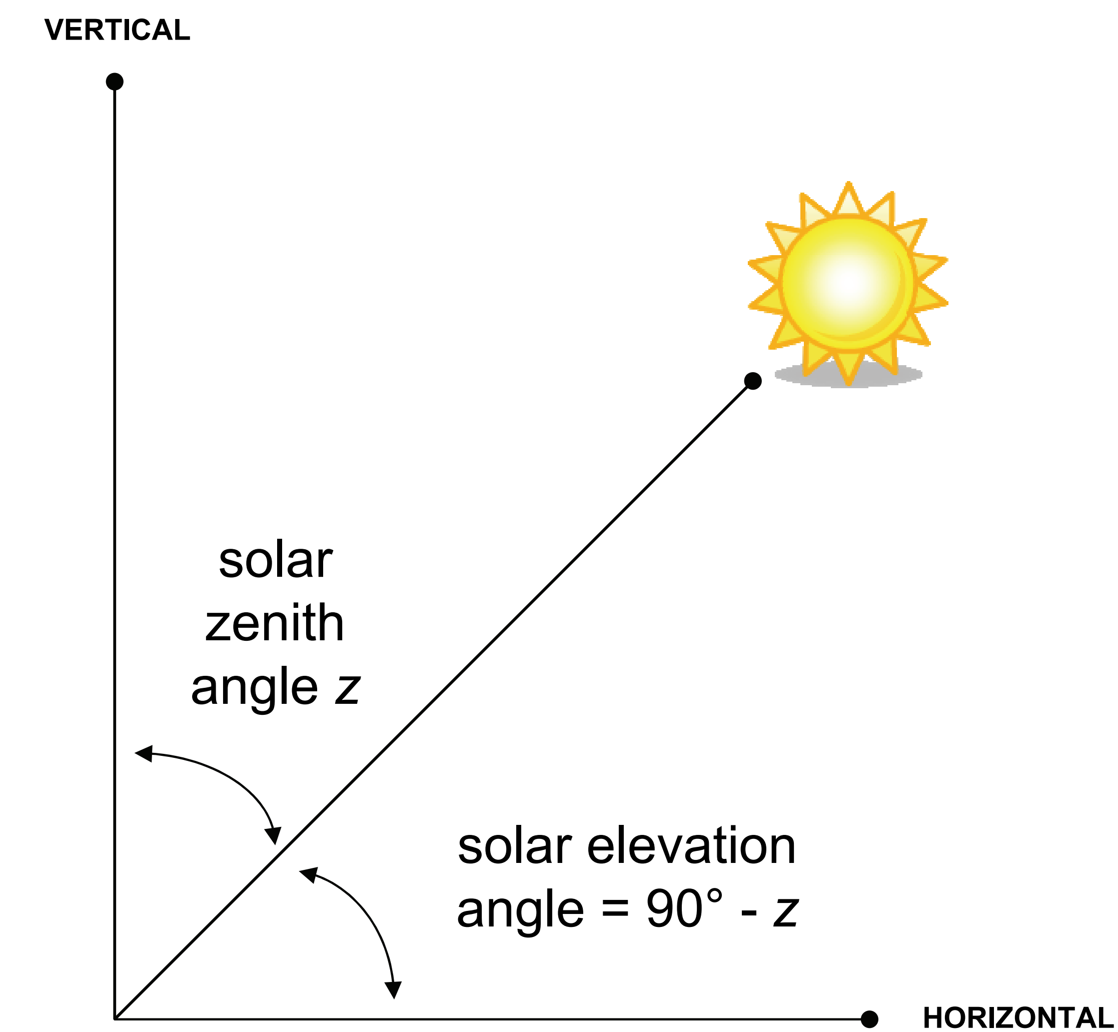
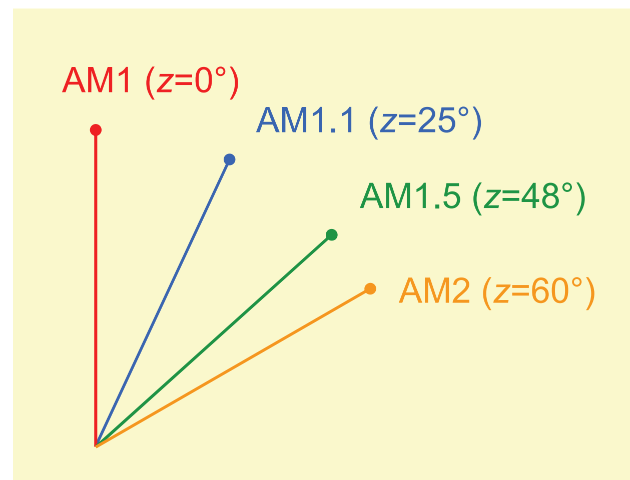
4. Introducing AM1GH irradiance, reflectance

Solar position and air mass

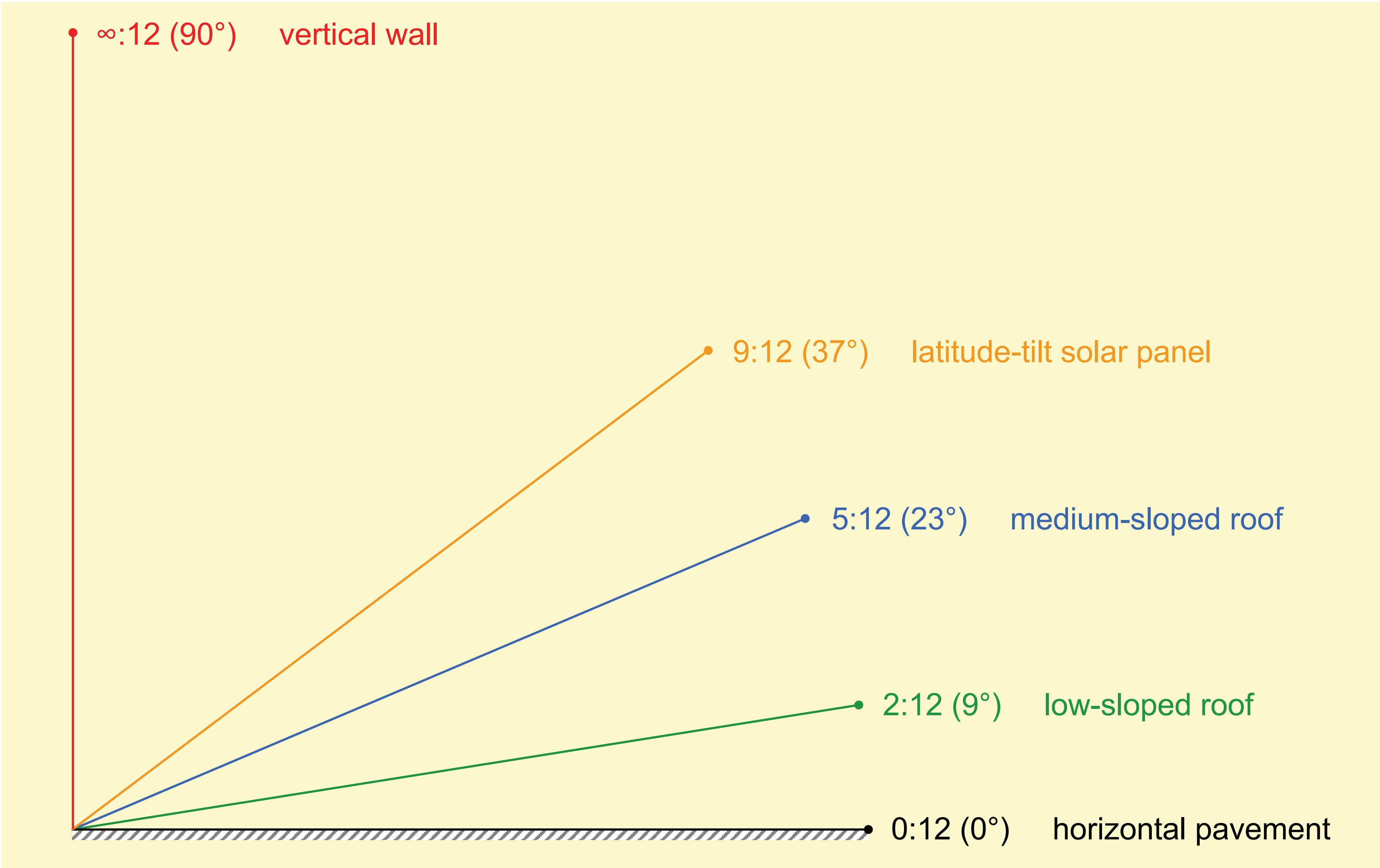


air mass ≡
atmospheric path length / height of atmosphere

air mass ≈ 1 / cos(z)



Tilts of common surfaces



Roof axisymmetry (i)

Roof axisymmetry (ii)

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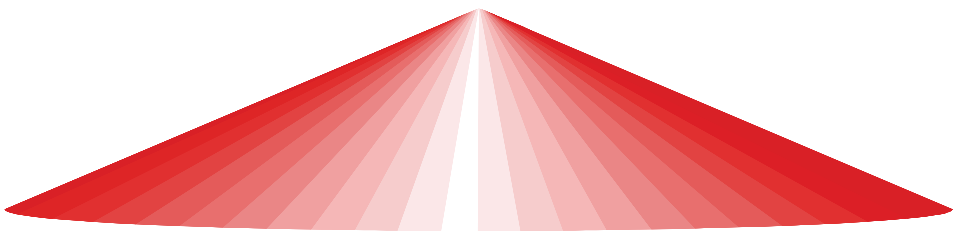
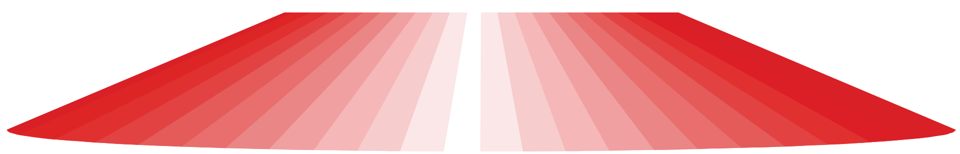
Simple axisymmetric surfaces



curved surface of cone (pitch 5:12)

curved surface of cylinder (vertical)

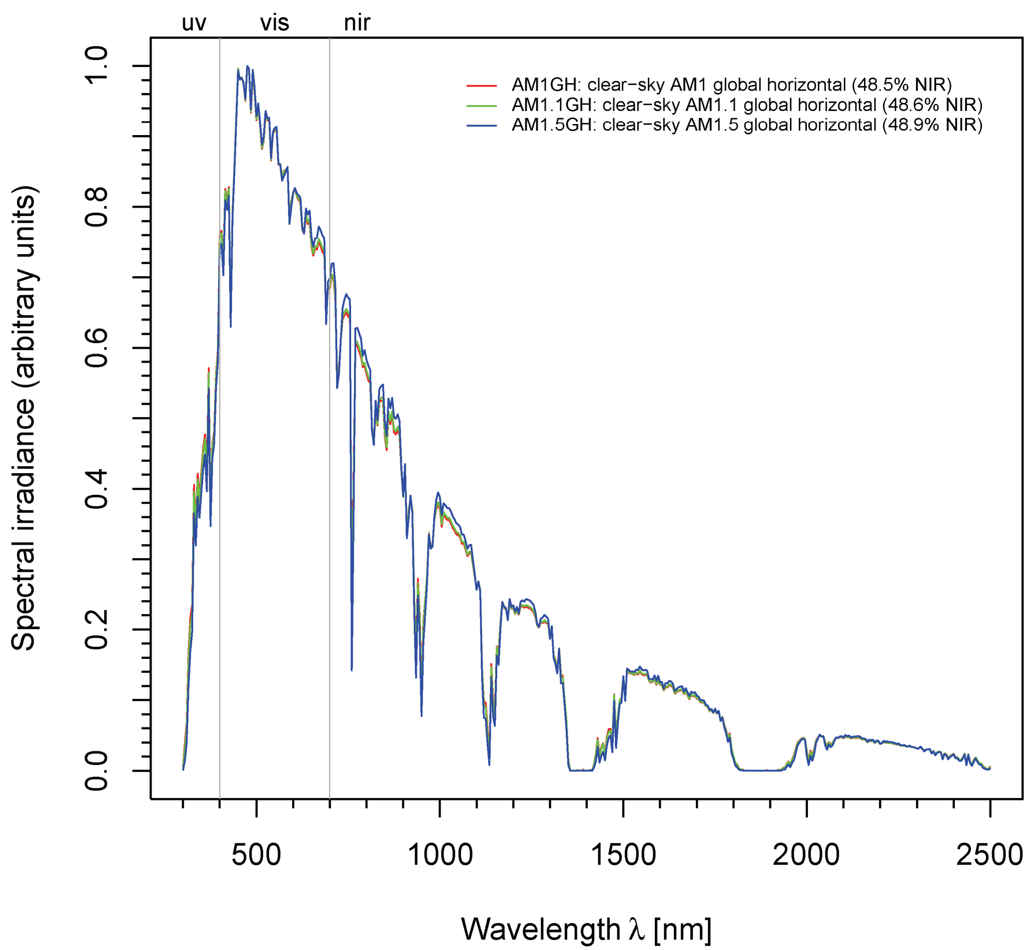


curved surface of truncated cone (pitch 5:12)

horizontal surface

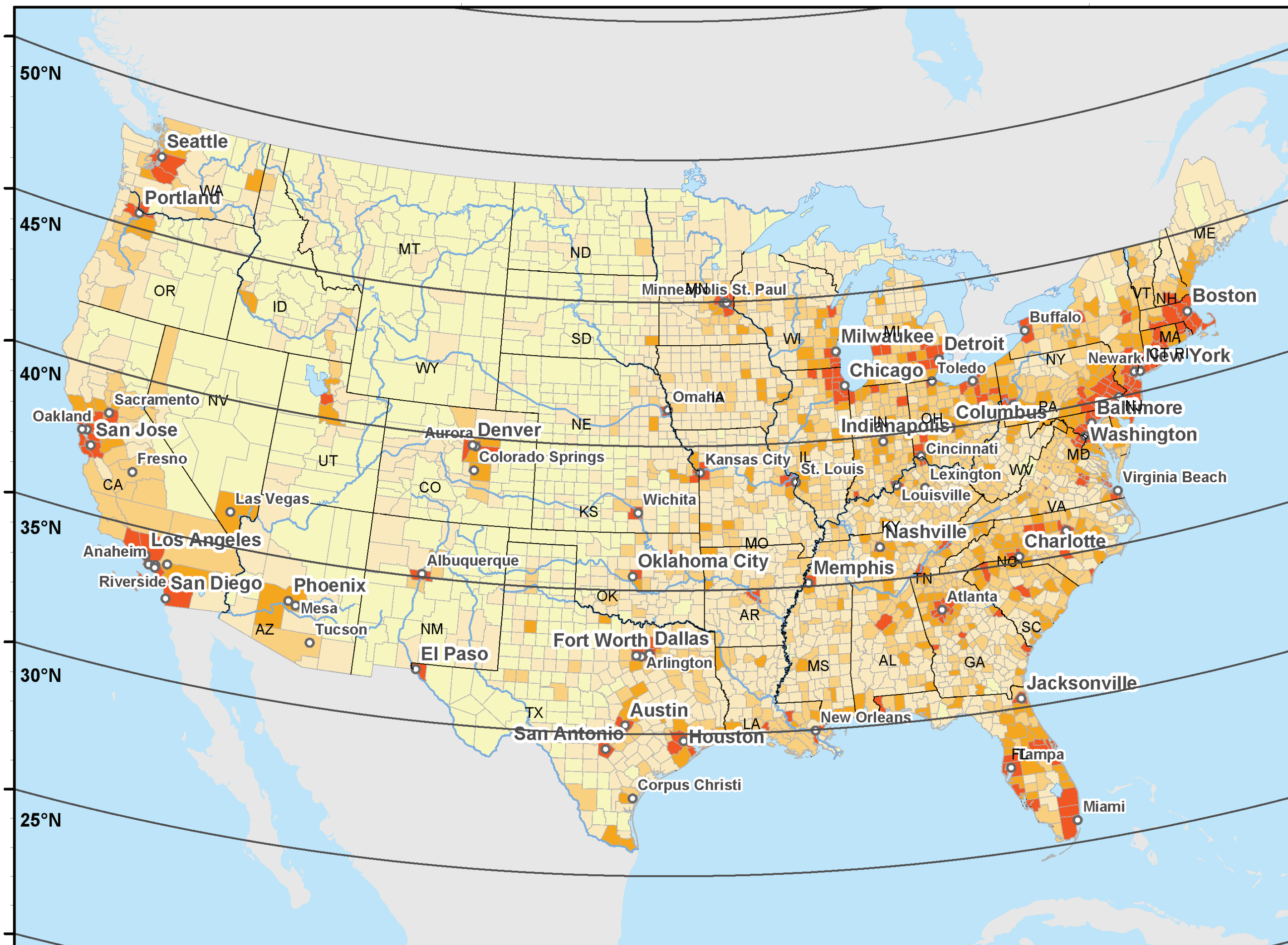
Choosing a reference solar spectral irradiance

- Ideal reference solar spectral irradiance i(λ) should
  - characterize annual peak global irradiance on roofs, pavements
  - apply to wide range of solar zenith angle *z*
  - be independent of solar azimuth angle
- AM1GH solar spectral irradiance
  - clear-sky
    Air Mass 1
    Global Horizontal
    solar spectral irradiance (*z*=0)
  - $i_{g,0}(\lambda)$



How high the sun? (i)

About 95% of U.S. population lives between 25°N and 45°N



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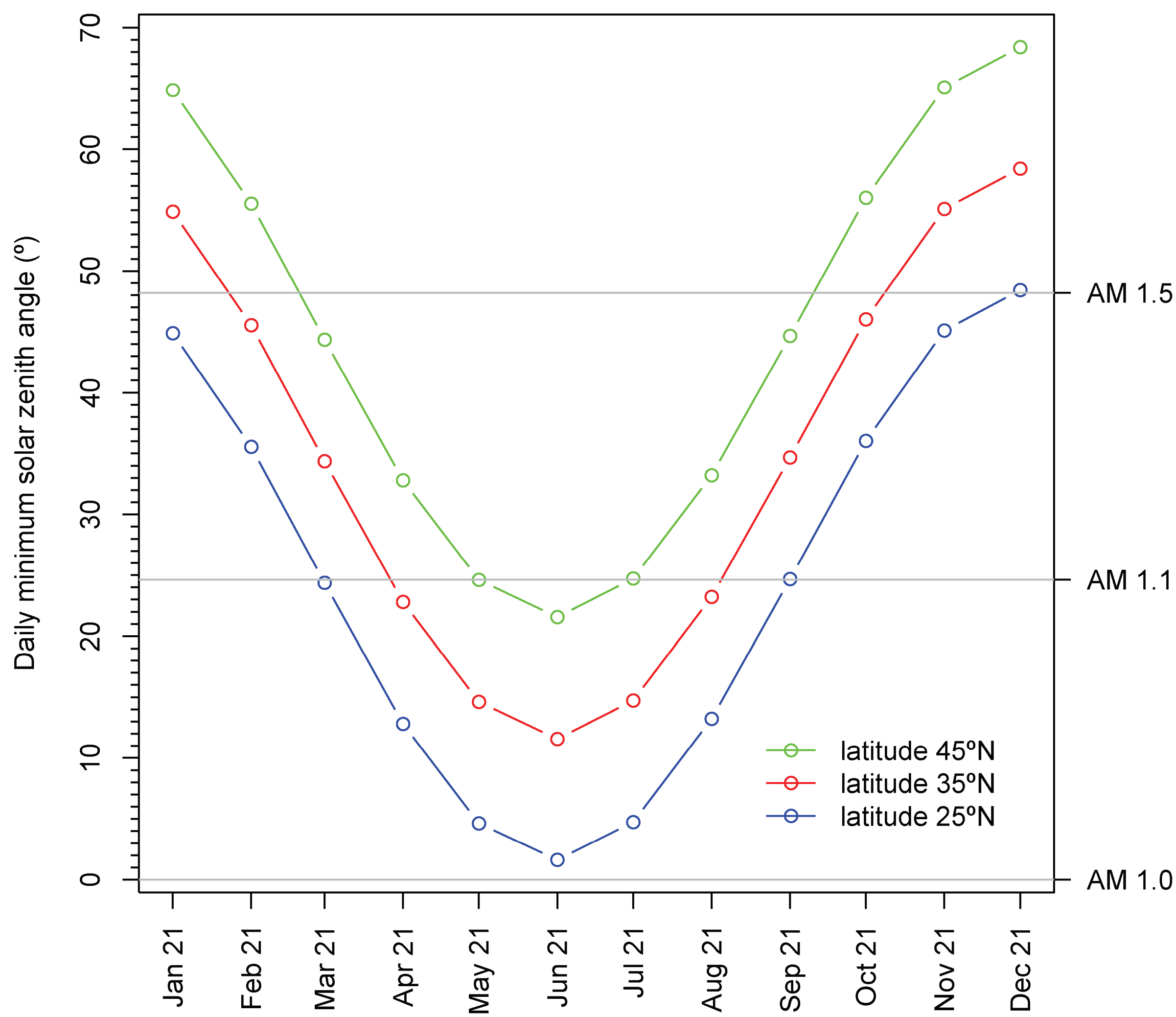
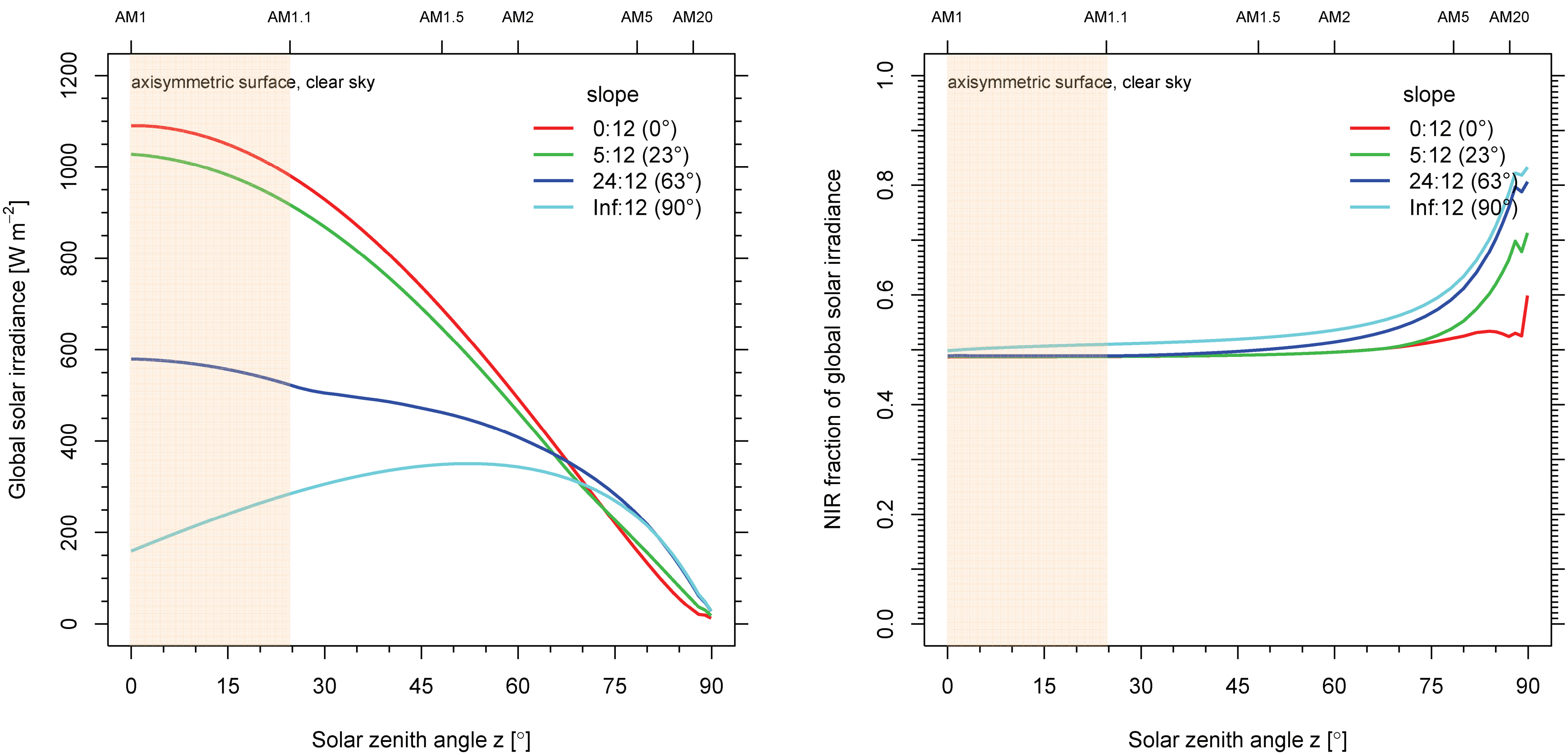
How high the sun? (ii)

Sun reaches AM1.1 (z=25°) 2, 4, 6 months at latitudes 45°N, 35°N, 25°N



$i_{g,0}(\lambda)$ useful at tilts up to 24:12 (63°)

…when applied to axisymmetric surfaces



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Choosing a reference solar reflectance

- Ideal reference solar reflectance R should
  - be evaluated at or near I_{peak} to reduce absolute solar heat gain error $|\Delta Q| = I\,|\Delta R|$
  - apply to wide range of solar zenith angle *z*
  - be independent of solar azimuth angle
- AM1GH *solar spectral* reflectance
  - clear-sky Air Mass 1 Global Horizontal solar spectral reflectance (*z*=0)
  - $r_{g,0}(\lambda)$

- AM1GH solar reflectance
  - clear-sky air mass 1 global horizontal solar reflectance (*z*=0)
  - $R_{g,0}$

$$R_{\mathrm{g},0} \equiv I_{\mathrm{g},0}^{-1} \int_{\mathcal{S}} i_{\mathrm{g},0}(\lambda)\, r_{\mathrm{g},0}(\lambda)\, d\lambda$$

$$I_{\mathrm{g},0} \equiv \int_{\mathcal{S}} i_{\mathrm{g},0}(\lambda)\, d\lambda$$

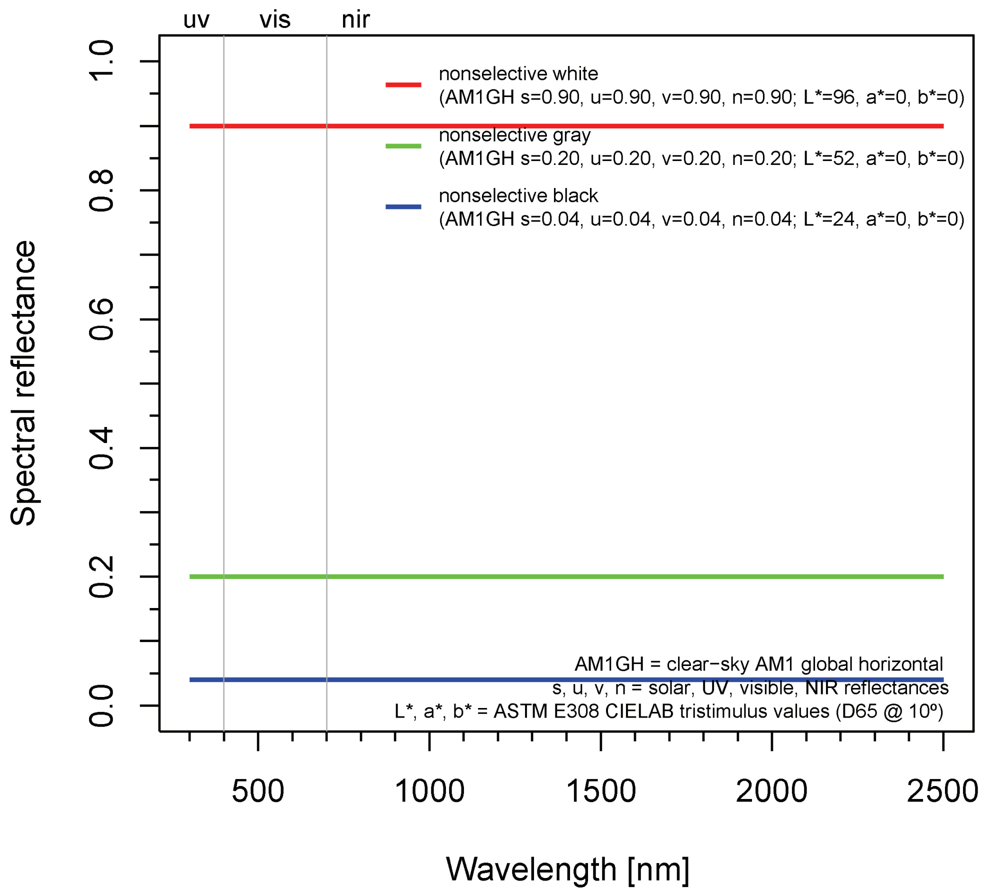
5. Calculation of solar heat gain

Irradiance and reflectance simulations

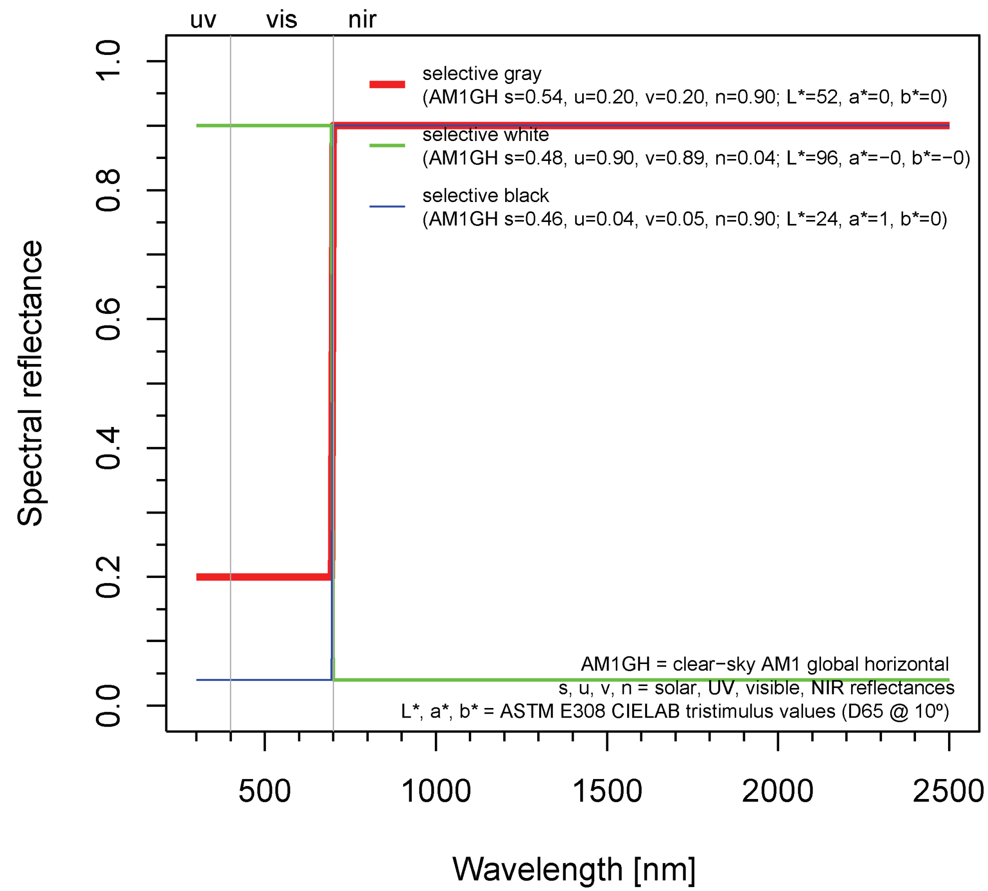
- NREL SMARTS 2.9.5 solar spectral irradiance model
- Solar zenith angle $z = 0 – 89.9°$
- Surface geometries
  - axisymmetric
  - 10 tilts (0 - 90°)
- Surface spectral reflectances
  - nonselective black, gray, white
  - selective black, gray, white
- Two reflectance models
  - matte (Lambertian)
  - glossy (image formed by first-surface reflection)
- Evaluate performance of $R_{g,0}$, R_{E891BN}
  - instantaneous, peak, seasonal errors in solar heat gain
  - summer, winter errors in solar reflectance gain when installing cool roof

Spectral reflectances of simulated surfaces

nonselective surfaces

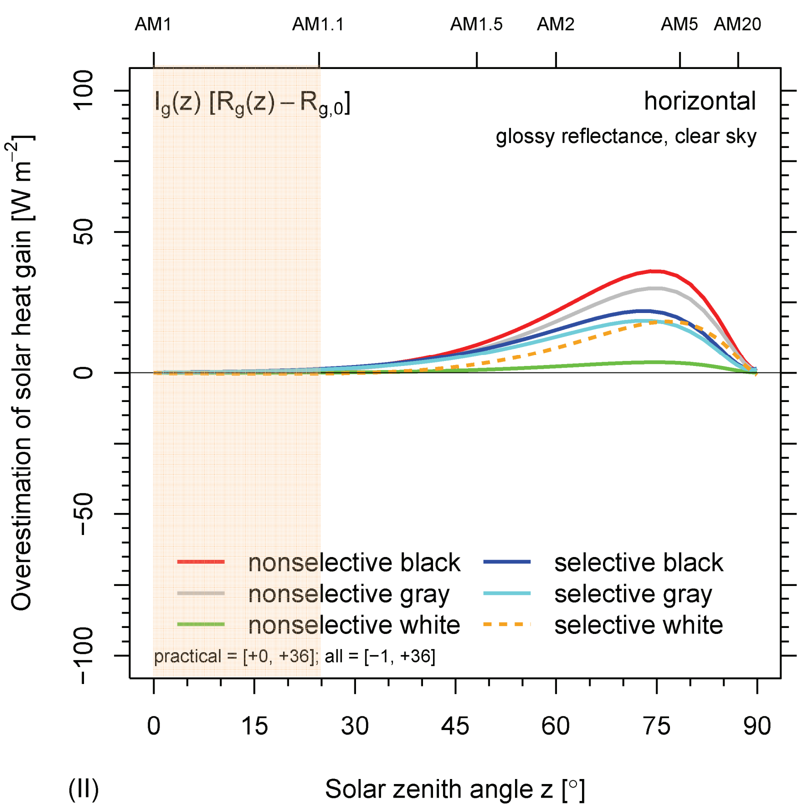


selective surfaces

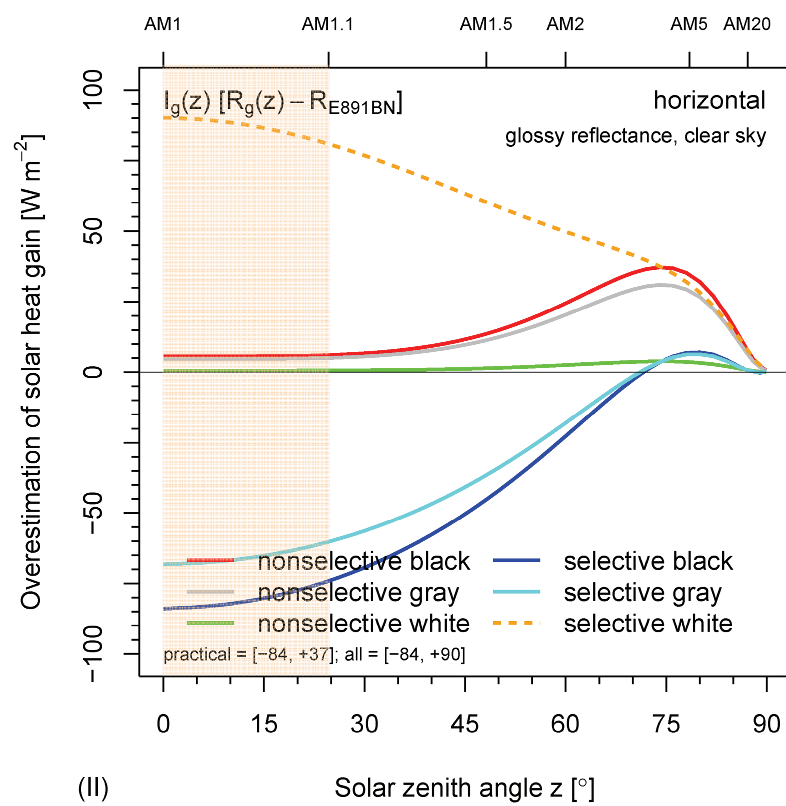


Errors in instantaneous solar heat gain

Using $R_{g,0}$

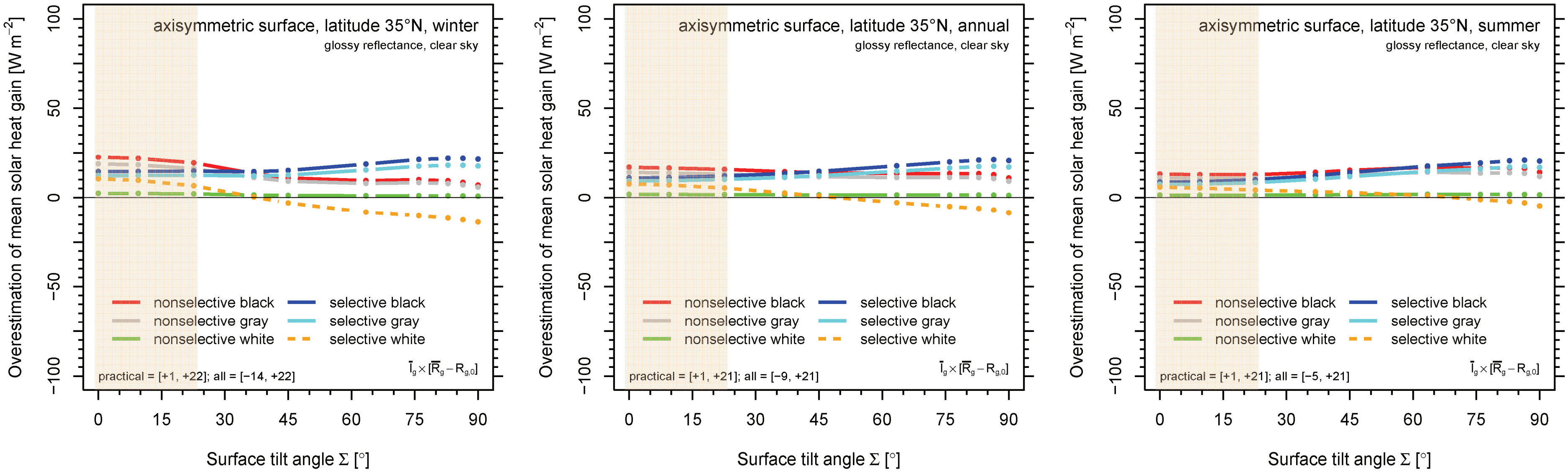


Using R_{E891BN}

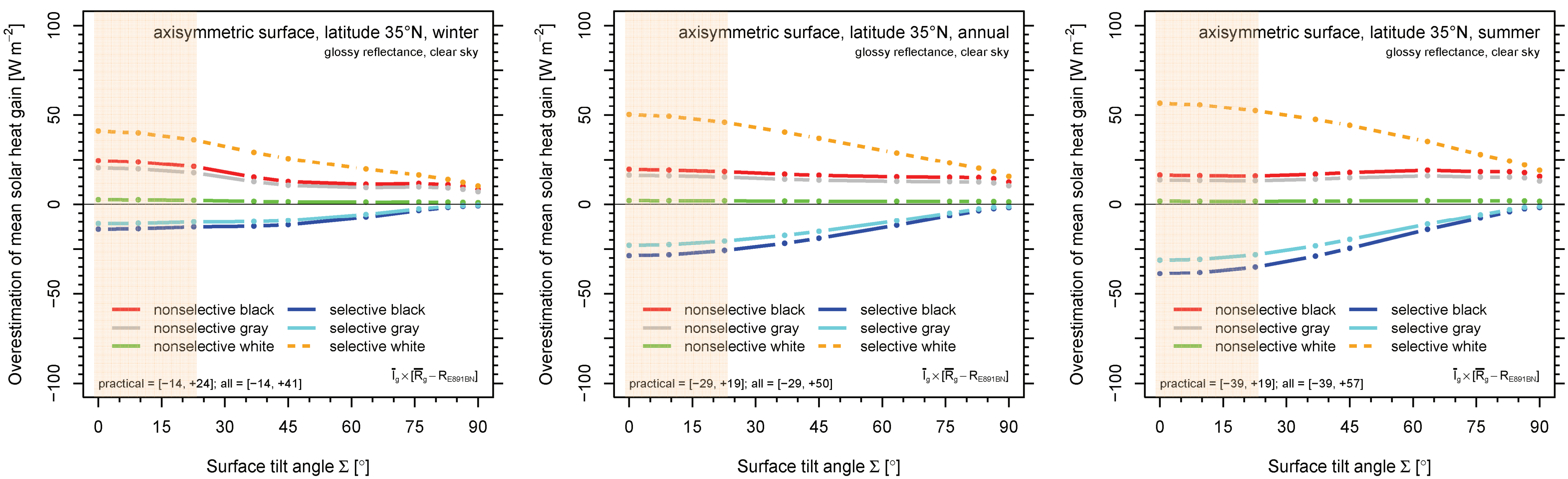


Errors in seasonal mean solar heat gains

Using $R_{g,0}$

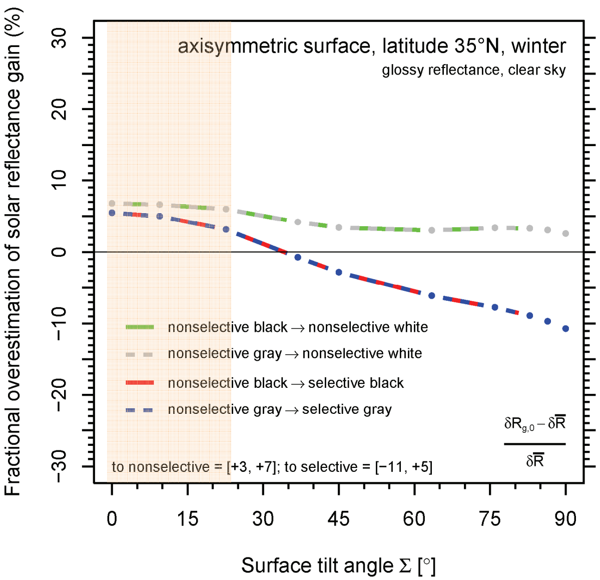


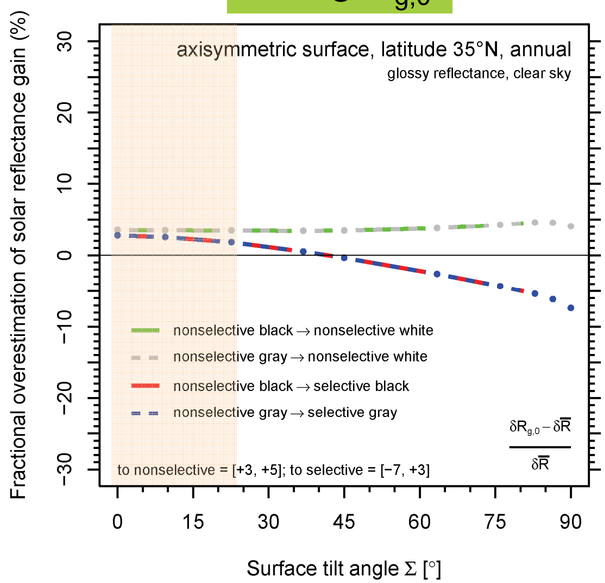
Using R_{E891BN}

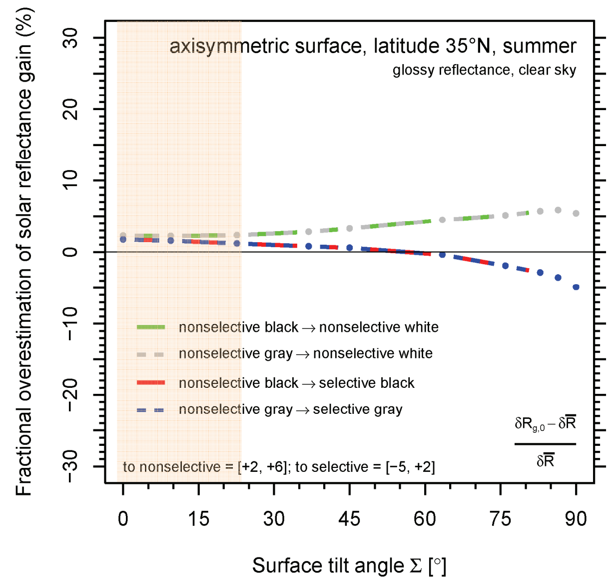


Fractional errors in solar reflectance gain

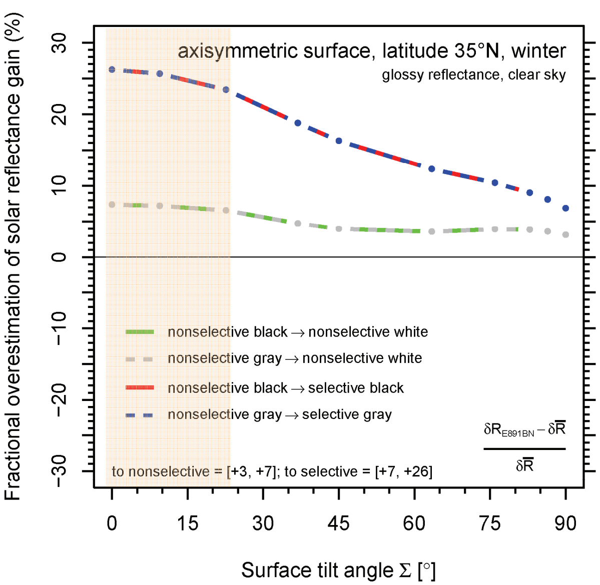
Using $R_{g,0}$

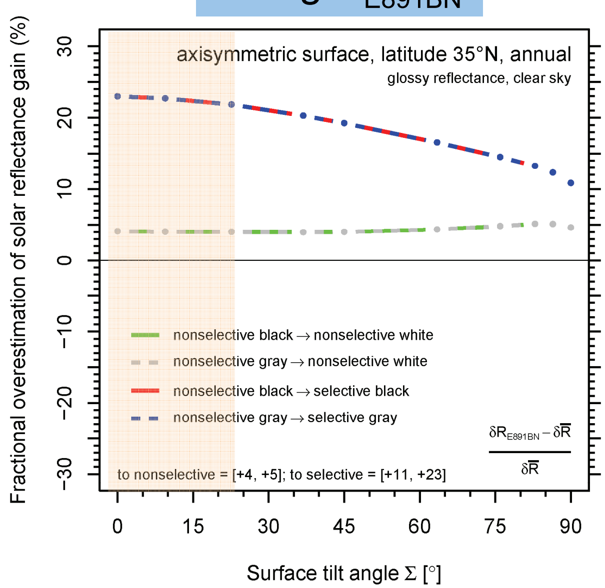


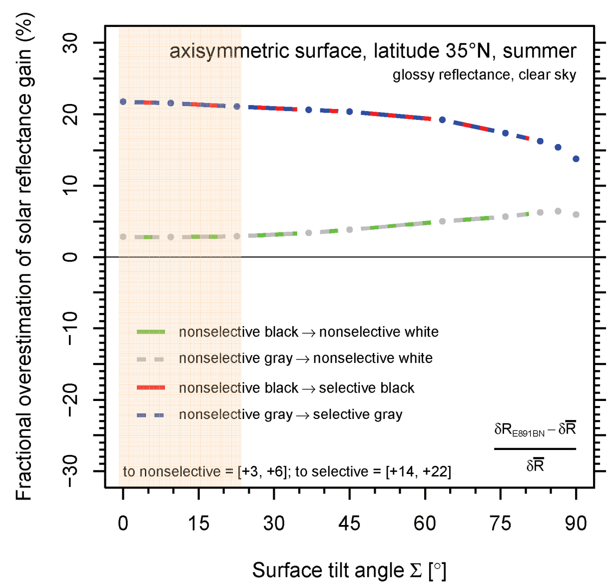




Using R_{E891BN}







Cool roof retrofit energy savings

- Assume
  - roof upgraded from standard color to cool color
  - annual cooling energy savings *C* ~ gain in summer mean solar reflectance
  - annual heating energy penalty *H* ~ gain in winter mean solar reflectance
- Net economic value of annual energy savings

$$N = C - H$$

- Annual building energy simulations
  - using R_{E891BN} for roof solar reflectance can overestimate *N* by up to 23%
  - using $R_{g,0}$ for roof solar reflectance overestimates *N* by no more than 3%

Summary: $R_{g,0}$ vs. R_{E891BN}

(for axisymmetric surfaces at tilts up to 5:12)

- $R_{g,0}$
  - predicts peak solar heat gain to within 1 W/m^2
  - overestimates annual mean solar heat gain by 2 to 19 W/m^2
  - overestimates net economic value of cool roof energy savings by no more than 3%

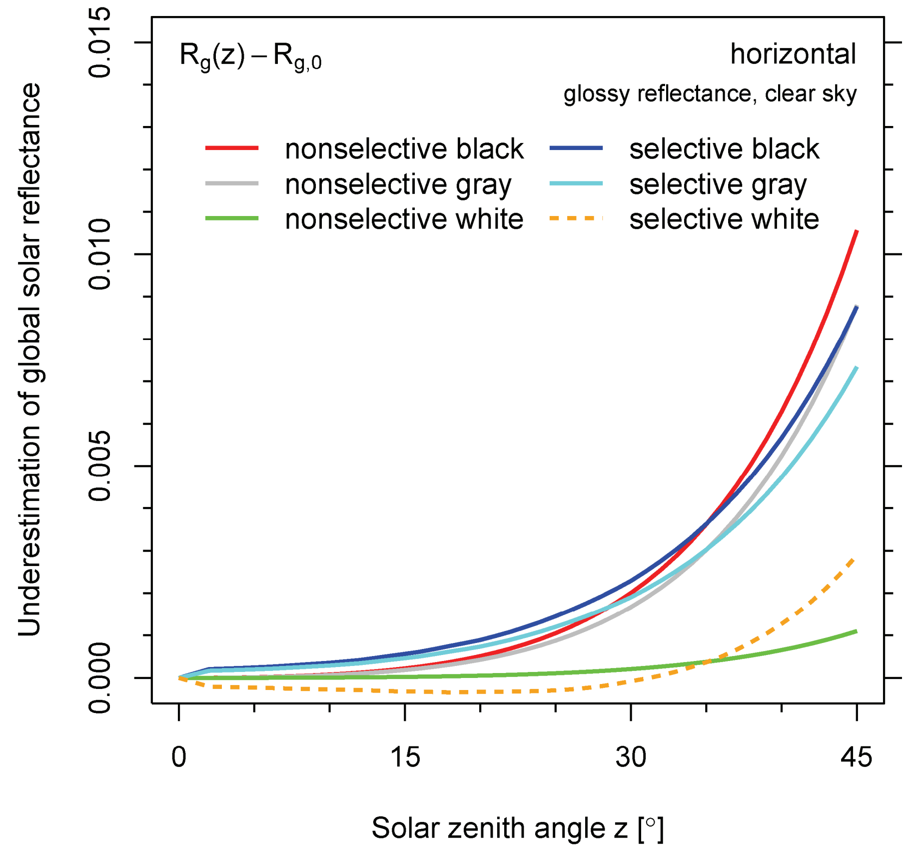
- R_{E891BN}
  - underestimates peak solar heat gain by up to 91 W/m^2
  - overestimates annual mean solar heat gain by -36 to 22 W/m^2
  - overestimates net economic value of cool roof energy savings by up to 23%

∴ $R_{g,0}$ better predicts solar heat gain and cool-roof energy savings

6. Measuring $R_{g,0}$

Pyranometer (E1918, E1918A)

- ASTM E1918-06
  - *Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field*
  - requires clear sky, $z < 45°$
  - neglecting shadow and background errors, $|R_{E1918} - R_{g,0}| \le 0.01$
- LBNL E1918A even better
  - reduces background, shadow errors



Solar spectrophotometer (E903)

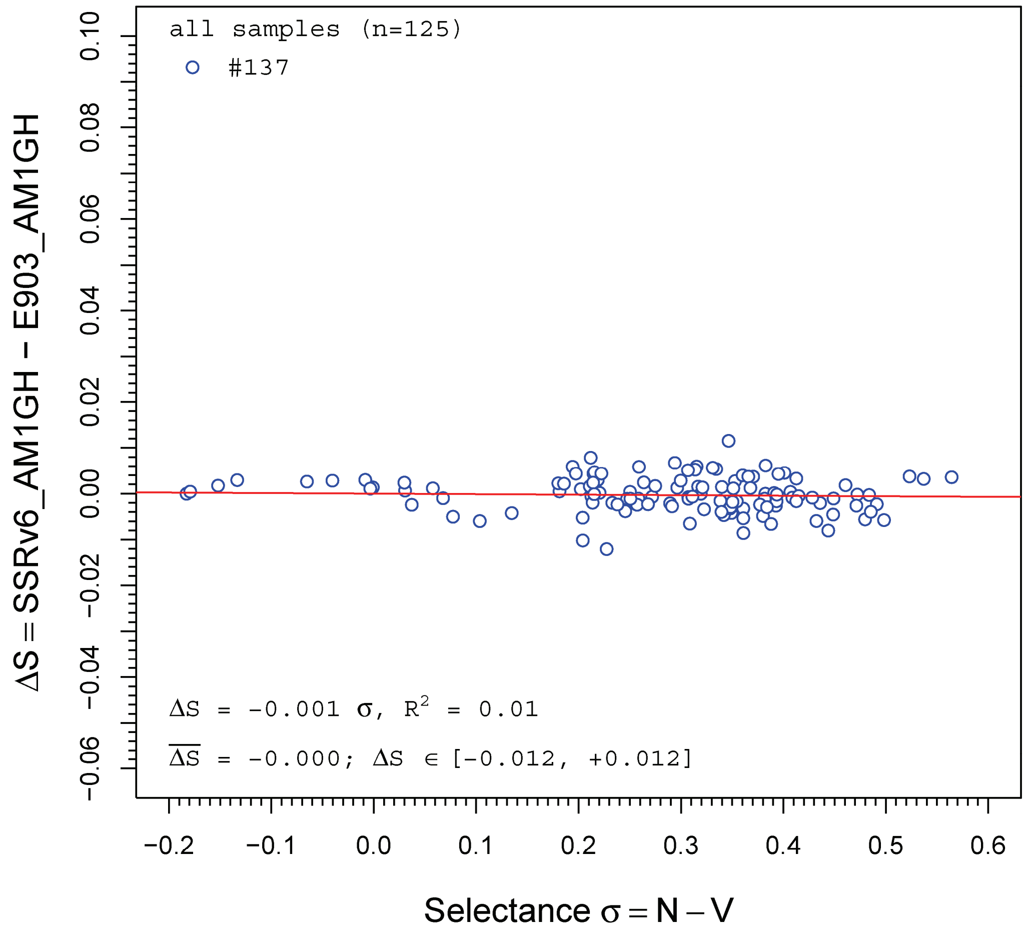
- ASTM E903-96 (withdrawn 2005)
  - *Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres*
  - weighting near normal-hemispherical solar spectral reflectance $r_{b,n}(\lambda)$ with $i_{g,0}(\lambda)$ yields $|R^*_{g,0} - R_{g,0}| \leq 0.006$
- Will advocate inclusion of $R^*_{g,0}$ calculation in next version of E903

$$R^*_{\mathrm{g,0}} \equiv I^{-1}_{\mathrm{g,0}} \int_{\mathcal{S}} i_{\mathrm{g,0}}(\lambda)\, r_{\mathrm{b,n}}(\lambda)\, d\lambda$$

$$I_{\mathrm{g,0}} \equiv \int_{\mathcal{S}} i_{\mathrm{g,0}}(\lambda)\, d\lambda$$

Solar Spectrum Reflectometer (C1549)

- ASTM C1549-04
  - *Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer*
  - collaborated with manufacturer (Devices & Services, Dallas, TX) to add several new reflectance outputs, including $R^*_{g,0}$
- SSRv6 measuring $R^*_{g,0}$ now available



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7. Publications

Two articles in press

- Levinson, R., H. Akbari and P. Berdahl. 2009. Measuring solar reflectance—Part I: defining a metric that accurately predicts solar heat gain. Submitted to *Progress in Solar Energy*.
- Levinson, R., H. Akbari and P. Berdahl. 2009. Measuring solar reflectance—Part II: review of practical methods. Submitted to *Progress in Solar Energy*.

Thanks for coming!