CAE 463/524
Building Enclosure Design
Spring 2016

Week 4: February 2, 2016
Solar orientation and solar radiation modeling

Built
Environment
Research
@ IIT

Advancing energy, environmental, and sustainability research within the built environment

www.built-envi.com

Twitter: @built_envi

Dr. Brent Stephens, Ph.D.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
brent@iit.edu

Updates

- No class last week (ASHRAE conference)
- Campus building enclosure project expectations are on BB
  - Need to select teams (next slides)
- New teaching assistant: Akram Ali
  - PhD candidate, Civil Engineering
  - Graduate research assistant, Built Environment Research Group
  - Email: aali21@hawk.iit.edu
  - Location: Alumni 217
- Job opportunities
- Assign HW 1 (due next Tues Feb 9)

Job opportunities

- Career fair: Thursday, February 4th
  - 12-4 pm Hermann Hall
  - https://web.iit.edu/career-services/employers/recruit-illinois-tech/career-fairs

- Building enclosure companies:
  - Wiss, Janney, Elstner Associates (WJE)
    - Contact: Elizabeth (Liz) Pugh
  - Permasteelisa
    - Contact: pna-recruiting@permasteelisagroup.com

Campus enclosure assessment projects

- Need to do thermal assessments by early/mid March
  - There are now 23 students in this class

Course	Name	Email	Major	Level
CAE463-01	Blat Tatay, Andrea	ablattat@hawk.iit.edu	ARCE	GR
CAE463-01	Curioni, Dina P.	dcurioni@hawk.iit.edu	ARCE	U5
CAE463-01	Jarma, David A.	djarma@iit.edu	ARCE	U4
CAE463-01	Jordan, Taylor L.	tjordan3@hawk.iit.edu	ARCE	U4
CAE463-01	Kane, Benjamin M.	bkane2@hawk.iit.edu	ARC3	GR
CAE463-01	Lim, Keonho	klim6@hawk.iit.edu	ARCE	U4
CAE463-01	Mitchell, Alexander R.	amitche8@hawk.iit.edu	ARCE	U4
CAE463-01	Panczak, Bianca J.	bpanczak@iit.edu	ARCE	U5
CAE463-01	Rice, Lindsey E.	lrice1@hawk.iit.edu	ARCE	U4
CAE463-01	Townley, Nina V.	ntownley@hawk.iit.edu	ARCE	U4
CAE524-01	Ashayeri Jahan Khanemloo, Mehdi	mashaye1@hawk.iit.edu	ARCH	GD
CAE524-01	Babaei Sonbolabadi, Kamal	kbabaeis@hawk.iit.edu	MAE	GD
CAE524-01	Cueto, Patrick Kevin M.	pcueto@hawk.iit.edu	ARCE	GR
CAE524-01	Del Pino Torres, Julia Del Rosario	jdelpino@hawk.iit.edu	ARCE	GR
CAE524-01	Faramarzi, Afshin	afaramar@hawk.iit.edu	CE	GD
CAE524-01	Foss, Stephen M.	sfoss1@hawk.iit.edu	ARCE	GR
CAE524-01	Qiu, Luanzhizi	lqiu7@hawk.iit.edu	ARCE	GR
CAE524-01	Sharghi, Ali	asharghi@hawk.iit.edu	CE	GD
CAE524-01	Sudhakaran, Naveen	nsudhaka@hawk.iit.edu	ARCE	GR
CAE524-01	Zhang, Xu	xzhan212@hawk.iit.edu	ARCE	GR
CAE524-02	Castro, Jose L.	jcastro6@hawk.iit.edu	ARCE	GR
CAE524-02	Dipietro, Salvatore D.	sdipietr@hawk.iit.edu	ARCE	GR
CAE524-02	Lee, JiWan	jlee232@hawk.iit.edu	CM	GR

Campus enclosure assessment projects

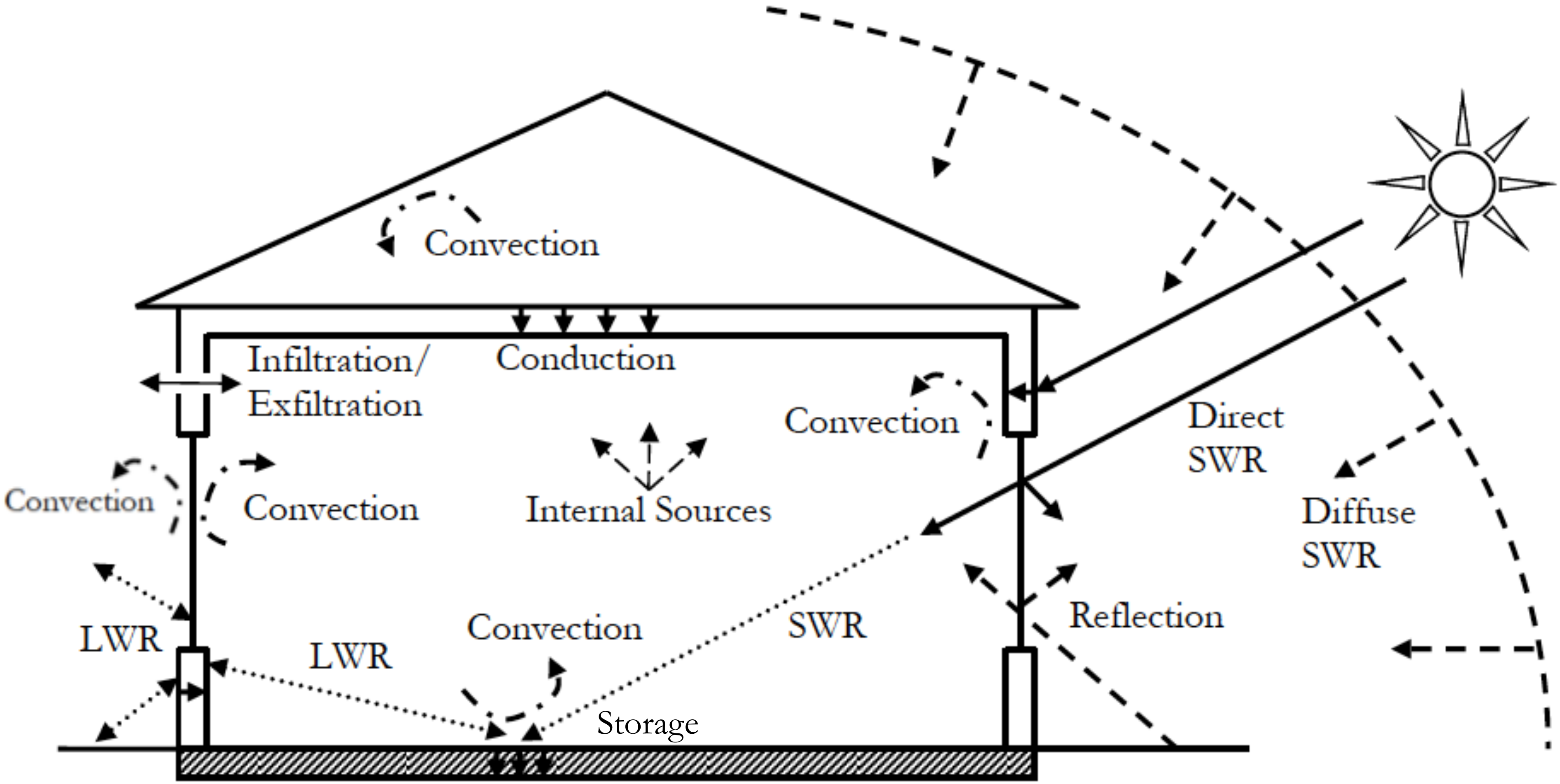
- Need to do thermal assessments by early/mid March
  - I suggest 5 teams of 4 or 5

Team #	Members	Building
1	Naveen, Julia, Xu, Luanzhizi	Alumni or Life Sciences
2	Bianca, Al, Taylor, David	SSV
3	Nina, Dina, Lindsey, Salvatore	Vandercook
4	Andrea,	Crown or Alumni

Review from last time

- Review of building science principles
  - Psychrometrics
  - Individual modes of heat transfer and fundamental properties
  - Bringing the modes together: surface energy balances

Building enclosures and heat transfer, visualized



Heat transfer in building science: Summary

Conduction

$$q = \frac{k}{L}\left(T_{surf,1} - T_{surf,2}\right)$$

$$\frac{k}{L} = U = \frac{1}{R}$$

$$R_{total} = \frac{1}{U_{total}}$$

$$R_{total} = R_1 + R_2 + R_3 + \ldots$$

For thermal bridges and combined elements:

$$U_{total} = \frac{A_1}{A_{total}} U_1 + \frac{A_2}{A_{total}} U_2 + \ldots$$

Convection

$$q_{conv} = h_{conv}\left(T_{fluid} - T_{surf}\right)$$

$$R_{conv} = \frac{1}{h_{conv}}$$

Radiation

Long-wave

$$q_{1\to 2} = \frac{\sigma\left(T_{surf,1}^4 - T_{surf,2}^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{A_1}{A_2}\frac{1-\varepsilon_2}{\varepsilon_2} + \frac{1}{F_{12}}}$$

$$q_{rad,1\to 2} = h_{rad}\left(T_{surf,1} - T_{surf,2}\right)$$

$$h_{rad} = \frac{4\sigma T_{avg}^3}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad R_{rad} = \frac{1}{h_{rad}}$$

Or more simply: $q_{1\to 2} = \varepsilon_{surf}\sigma F_{12}\left(T_{surf,1}^4 - T_{surf,2}^4\right)$

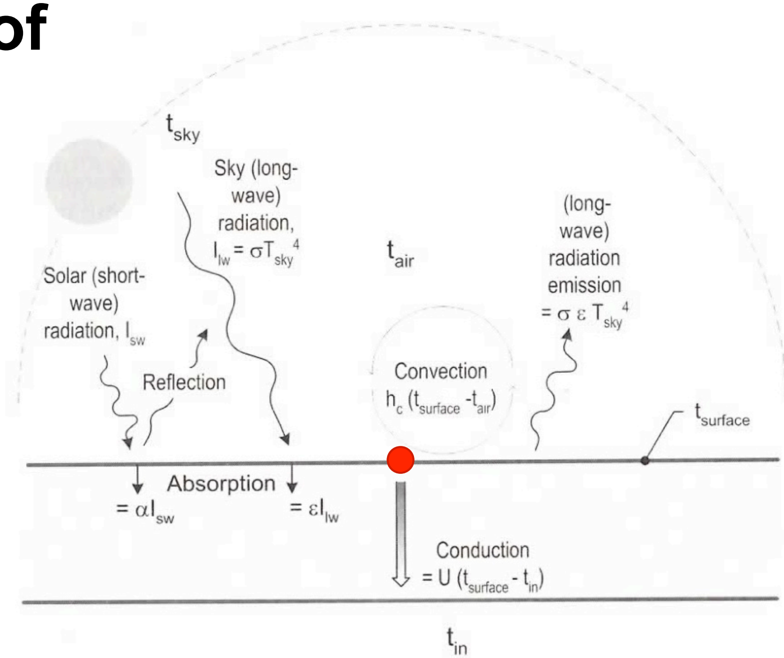
Solar radiation: (opaque surface) $q_{solar} = \alpha I_{solar}$

Transmitted solar radiation: (transparent surface) $q_{solar} = \tau I_{solar}$

Surface energy balance: Bringing all the modes together

- Exterior surface example: **Roof**

$$\boxed{\sum q = 0}$$



We can use this equation to estimate indoor and outdoor surface temperatures

At steady state, net energy balance is zero

- Because of T⁴ term, often requires iteration

Solar gain	αI_{solar}	$q_{sw,solar}$
Surface-sky radiation	$+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surface}^4)$	$+q_{lw,surface-sky}$
Convection on external wall	$+h_{conv}(T_{air} - T_{surface})$	$+q_{convection}$
Conduction through wall	$-U(T_{surface} - T_{surface,interior}) = 0$	$-q_{conduction} = 0$

Roof surface temperature example

Surface energy balance	Add	Subtract
	W/m^2	W/m^2
Solar (short-wave)	900	
Surface-sky long-wave radiation	-338	
Convection on roof	-551	
Conduction through roof		11
SUM	0	

Given	alpha	0.9	bituminous membrane		
Given	Itotal, W/m2	1000			
Assume	Fsurface-sky	1			
Assume	e,surface	0.9			
Given	Tair,out, K	293.15	20	degC	
Assume	Tair,out,dewpoint, K	275.06	1.91	degC	*psych chart*
Calculate	e,sky	0.79	N = 0		
Calculate	Tsky, K	276.61	Tsky equation for clear day		
Guess	**Tsurface, K**	**334.25**	**61.1**	**degC**	
Given	Tsurf,in, K	295.15	22.0	degC	
Constant	stef-boltz, W/(m2K4)	5.6704E-08			
Calculate	hconv, Wm2K	13.4			
Given	R-value IP, h-ft2-F/Btu	20			
Given	R-value, SI	3.52			
Given	U-value, W/m2K	0.28			

Adjust $T_{surface}$ until sum of all heat transfer modes equals zero

Roof surface temperature example (low absorptivity)

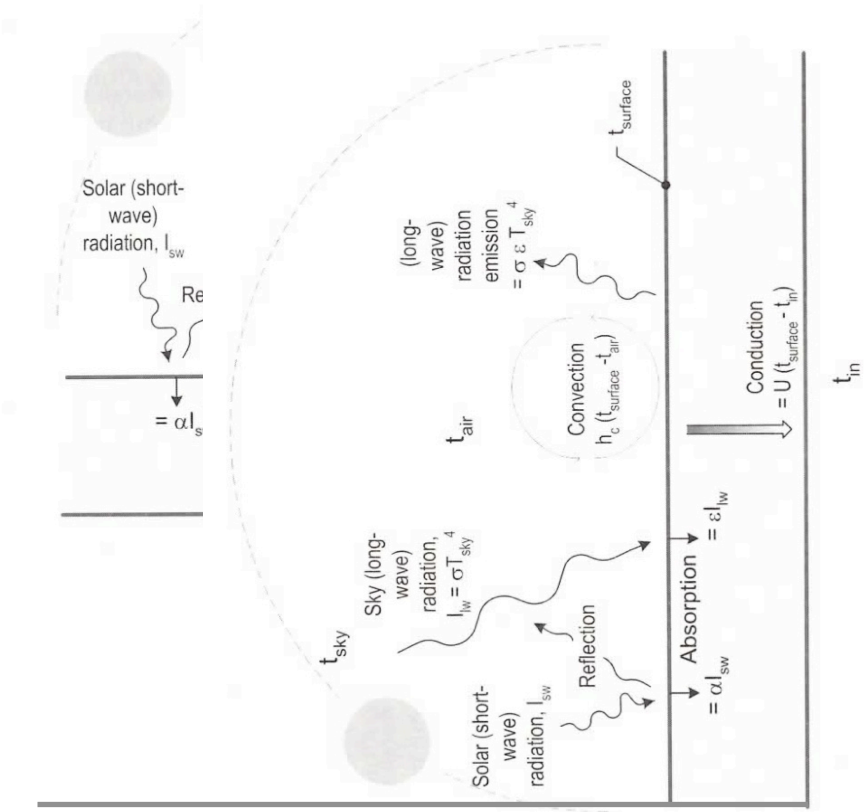
Surface energy balance	*Add*	*Subtract*
	W/m^2	W/m^2
Solar (short-wave)	300	
Surface-sky long-wave radiation	-141	
Convection on roof	-155	
Conduction through roof		3
SUM	0	

Given	alpha	0.3	bituminous membrane		
Given	Itotal, W/m2	1000			
Assume	Fsurface-sky	1			
Assume	e,surface	0.9			
Given	Tair,out, K	293.15	20	degC	
Assume	Tair,out,dewpoint, K	275.06	1.91	degC	*psych chart*
Calculate	e,sky	0.79	N = 0		
Calculate	Tsky, K	276.61	Tsky equation for clear day		
Guess	**Tsurface, K**	**304.75**	**31.6**	**degC**	
Given	Tsurf,in, K	295.15	22.0	degC	
Constant	stef-boltz, W/(m2K4)	5.6704E-08			
Calculate	hconv, Wm2K	13.4			
Given	R-value IP, h-ft2-F/Btu	20			
Given	R-value, SI	3.52			
Given	U-value, W/m2K	0.28			

Bringing all the modes together

- Similarly, for a vertical surface:

$$q_{solar} + q_{lwr} + q_{conv} - q_{cond} = 0$$



Ground

$$\alpha I_{solar}$$

$$+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surface}^4)$$

$$+\varepsilon_{surface}\sigma F_{ground}(T_{ground}^4 - T_{surface}^4)$$

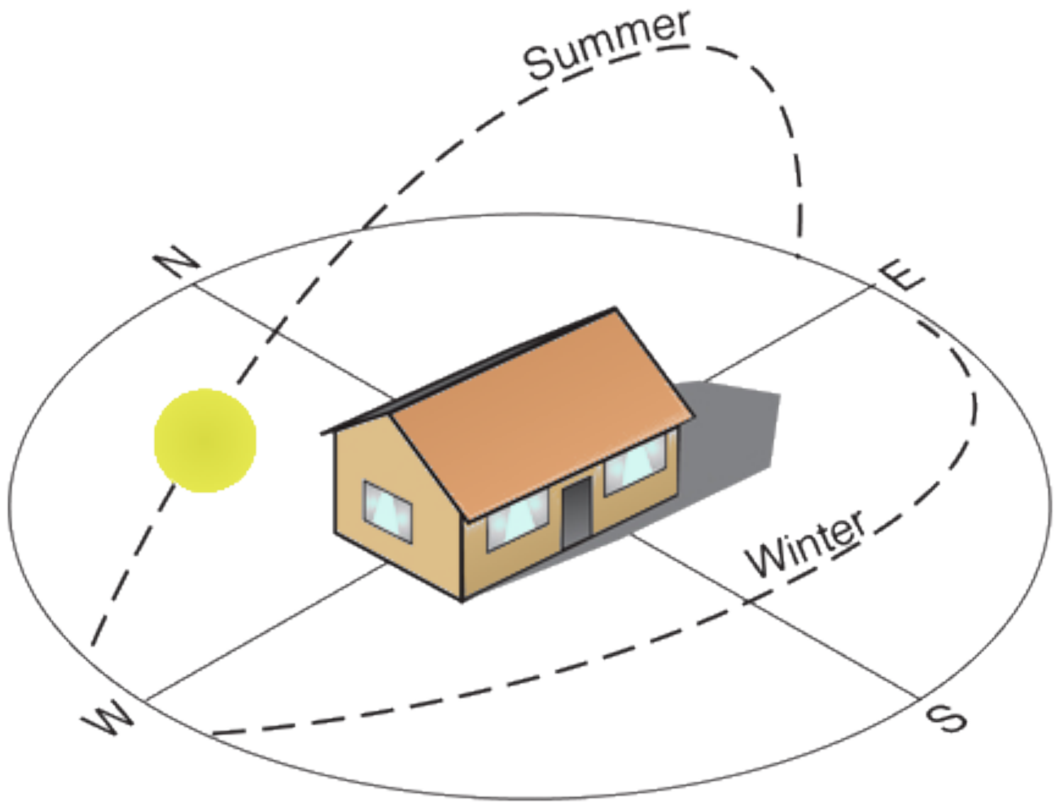
$$+h_{conv}(T_{air} - T_{surface})$$

$$-U(T_{surface} - T_{surface,interior}) = 0$$

Today's objectives

- Solar orientation and enclosures

- Assign HW #1



SOLAR ORIENTATION

Chicago: Sunrise to sunset

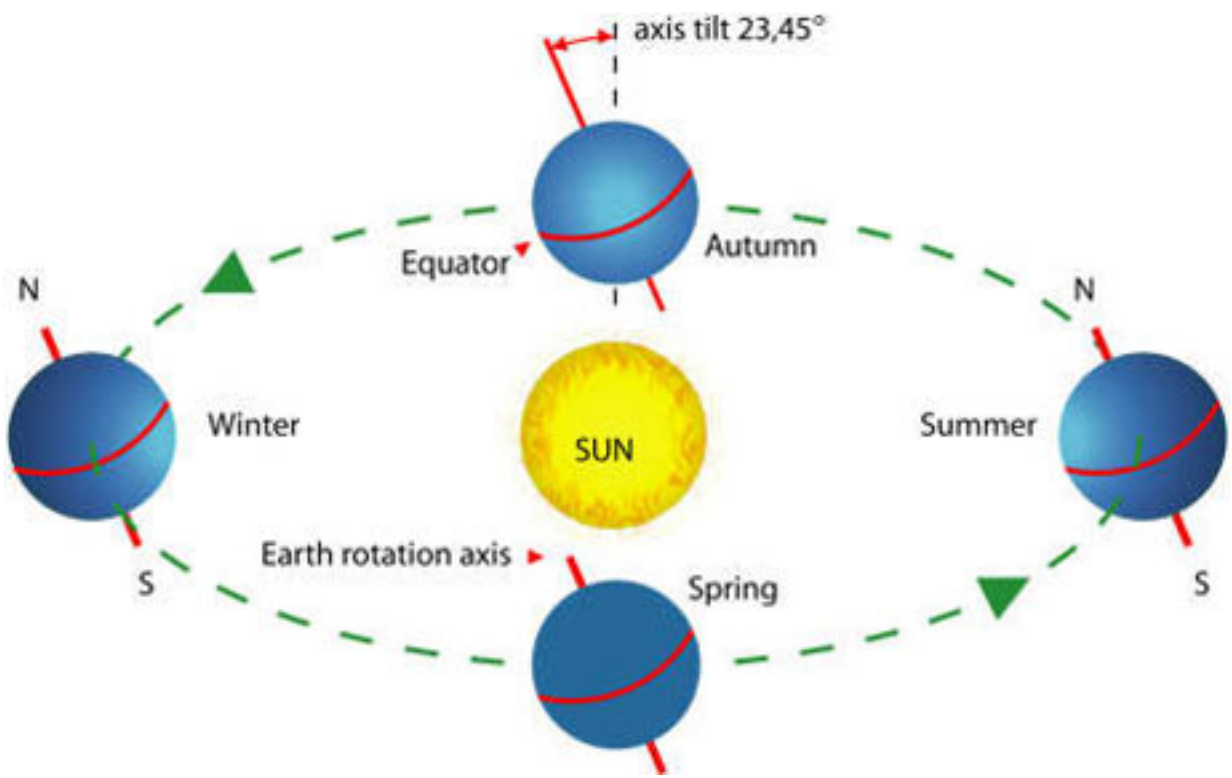
https://www.youtube.com/watch?v=xPGwhTUbJgQ

Solar radiation

- The sun is the source of most energy on the earth
- We need to have a working knowledge of earth's relationship to the sun
- We should be able to estimate solar radiation intensity
  - To understand thermal effects of solar radiation and how to control or utilize them:
  - We need to estimate solar gains on a building, and
  - We need to predict intensity of solar radiation and the direction at which it strikes building surfaces
    - It starts with relationships between the sun and the earth

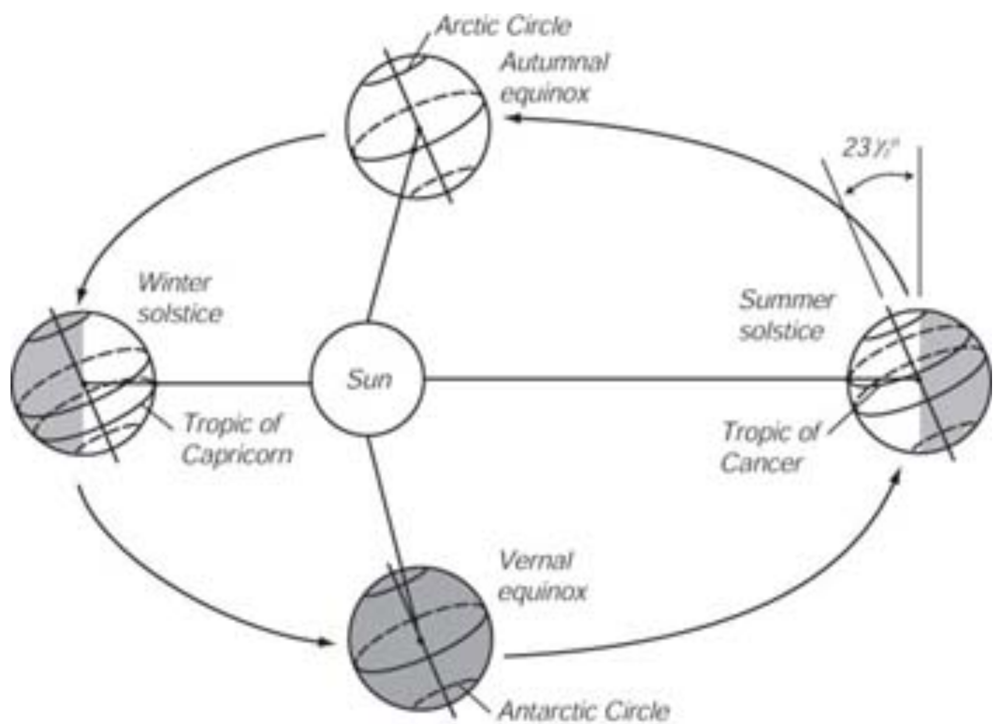
Solar radiation: earth-sun relationship

- Earth rotates about its axis every 24 hours
- Earth revolves around sun every 365.2425 days
- Earth is titled at an angle of 23.45°



Solar radiation: earth-sun relationship

- Therefore, different locations on earth receive different levels of solar radiation during different times of the year (and different times of the day)
  - The greatest amount of solar radiation is delivered to northern hemisphere on **June 21**
  - Least amount of solar energy delivered on **December 21**
- There are methods of determining the amount of flux of solar radiation to surfaces on the earth



Earth-sun relationships

- The position of a point P on the earth's surface with respect to the sun's rays can be calculated if we know:
  - Latitude of point on earth, l (degrees)
  - Hour angle of the point on earth, h (degrees)
  - Sun's declination, d (degrees)

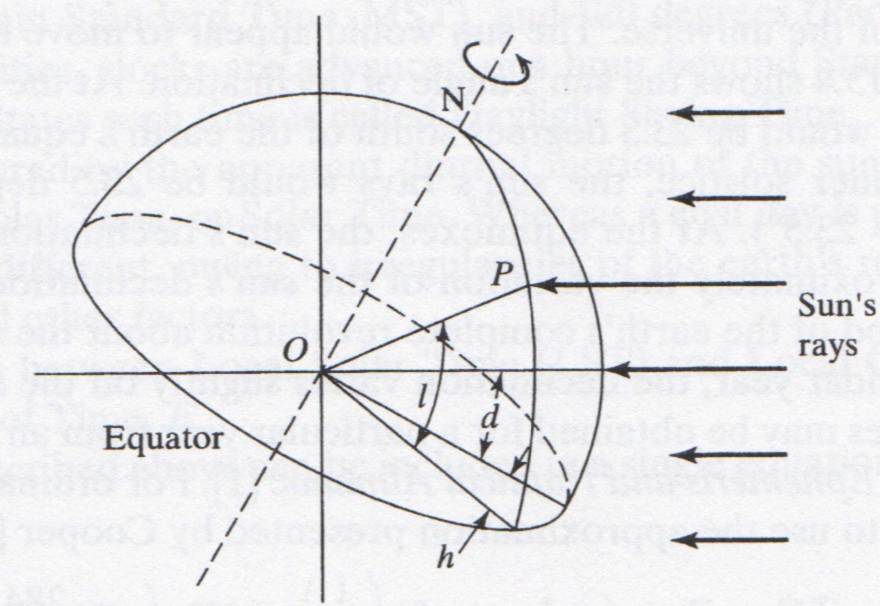


Figure 13.3 Latitude, hour angle, and sun's declination.

Earth-sun relationships

- Sun's declination, d, can be estimated by:

$$d = 23.45 \sin\left(360 \frac{284 + n}{365}\right)$$

Where n is the day of the year, which you can determine by counting on your hands, looking up online, or using this table:

TABLE 13.1 Variation in n throughout the Year for Eq. (13.1)

Month	n for the Day of the Month, D	Month	n for the Day of the Month, D
January	D	July	$181 + D$
February	$31 + D$	August	$212 + D$
March	$59 + D$	September	$243 + D$
April	$90 + D$	October	$273 + D$
May	$120 + D$	November	$304 + D$
June	$151 + D$	December	$334 + D$

Where D is the day of the month

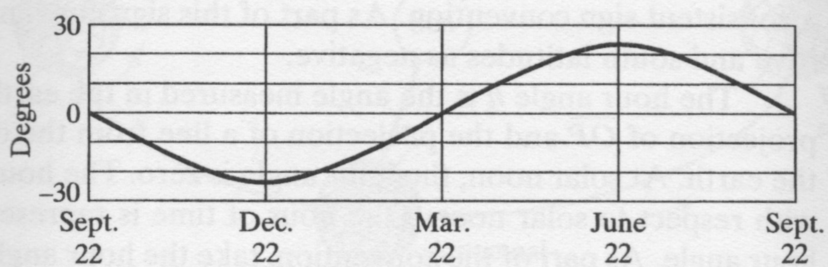
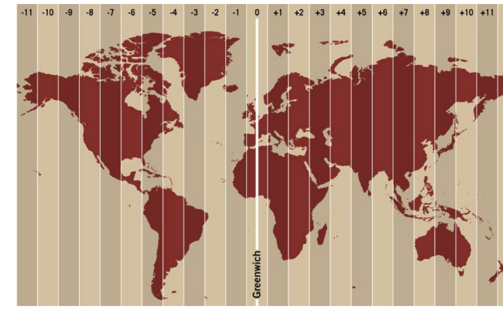


Figure 13.5 Variation of sun's declination.

d is **positive** when sun's rays are **north** of the equator

Earth-sun relationships

GCT



- Now we have latitude (l) and sun's declination (d)
  - Need hour angle (h)

It's all about **time**:

- Greenwich Civil Time = time at line of zero longitude
- Local Civil Time (CT) is governed by your longitude
  - $1/15^{th}$ of an hour (4 mins) of time for each degree difference in longitude
    - Central Standard Time is 90 degrees from 0
    - 4 min per degree * 90 degrees = 360 minutes = 6 hours
- Time is also measured by apparent diurnal motion of the sun
  - Apparent Solar Time (AST), Local Solar Time (LST), or Solar Time (ST)
    - Interchangeable terms
  - Slightly different than a civil day because of irregularities of the earth's rotation and shape of earth's orbit
  - The difference between solar time (LST) and civil time (CT) is called the **Equation of Time (E)**

Calculating solar time (LST)

- Local **solar** time (LST):

$$LST = CT + \left(\frac{1}{15}\right)(L_{std} - L_{loc}) + E - DT$$

Where:
LST = local solar time (hour)
CT = clock time (hour)
L_{std} = standard meridian longitude for local time zone (degrees west)
L_{loc} = longitude of actual location (degrees west)
E = Equation of Time (hour)
DT = Daylight savings time correction (hour)
*DT = 1 if on DST; otherwise 0

**Note that all times should be converted to decimal format from 0 to 24. For example, 3:45 PM = 15.75 hours

- Equation of Time: $E = 0.165 \sin 2B - 0.126 \cos B - 0.025 \sin B$

where $B = \frac{360(n - 81)}{364}$ and n is the day of the year. *B* is in degrees

Calculating solar time (LST)

- Finally, the solar hour angle, h, can be calculated:

$$h = 15(\text{LST} - 12) \text{ degrees}$$

h is **positive *after*** solar noon and **negative *before***

LST is in 24 hour format

- Again, you can either calculate these values, use a website*, or look them up in a table like this:

TABLE 13.2 The Sun's Declination and Equation of Time, Calculated

	Day 7		Day 14		Day 21		Day 28	
Month	Declination, Degrees	Eq. of Time, Hours	Declination, Degrees	Eq. of Time, Hours	Declination, Degrees	Eq. of Time, Hours	Declination, Degrees	Eq. of Time, Hours
January	−22.4	−0.10	−21.4	−0.15	−20.1	−0.19	−18.5	−0.22
February	−15.8	−0.24	−13.6	−0.24	−11.2	−0.24	−8.7	−0.22
March	−6.0	−0.20	−3.2	−0.17	−0.4	−0.13	2.4	−0.09
April	6.4	−0.04	9.0	−0.01	11.6	0.02	13.9	0.04
May	16.7	0.06	18.5	0.06	20.1	0.06	21.4	0.05
June	22.7	0.02	23.3	0.00	23.45	−0.03	23.3	−0.05
July	22.6	−0.08	21.7	−0.09	20.4	−0.10	18.9	−0.10
August	16.3	−0.09	14.1	−0.07	11.8	−0.04	9.2	−0.01
September	5.4	0.05	2.6	0.09	−0.2	0.13	−3.0	0.17
October	−6.6	0.22	−9.2	0.25	−11.8	0.27	−14.1	0.27
November	−17.1	0.27	−18.9	0.25	−20.4	0.22	−21.7	0.18
December	−22.8	0.12	−23.3	0.07	−23.45	0.02	−23.3	−0.04

*NOAA has website for this: http://www.esrl.noaa.gov/gmd/grad/solcalc/

Calculating solar time (LST) and hour angle (h)

- Example problem:
- Determine the local solar time and sun's hour angle in Minneapolis, MN (44.9° N, 93.3° W) at 2:25 PM Central Daylight Savings Time on July 21

Earth-sun relationships

- Once we have our local latitude l, the sun's declination angle d, and the hour angle h, we can move on to other important relationships:

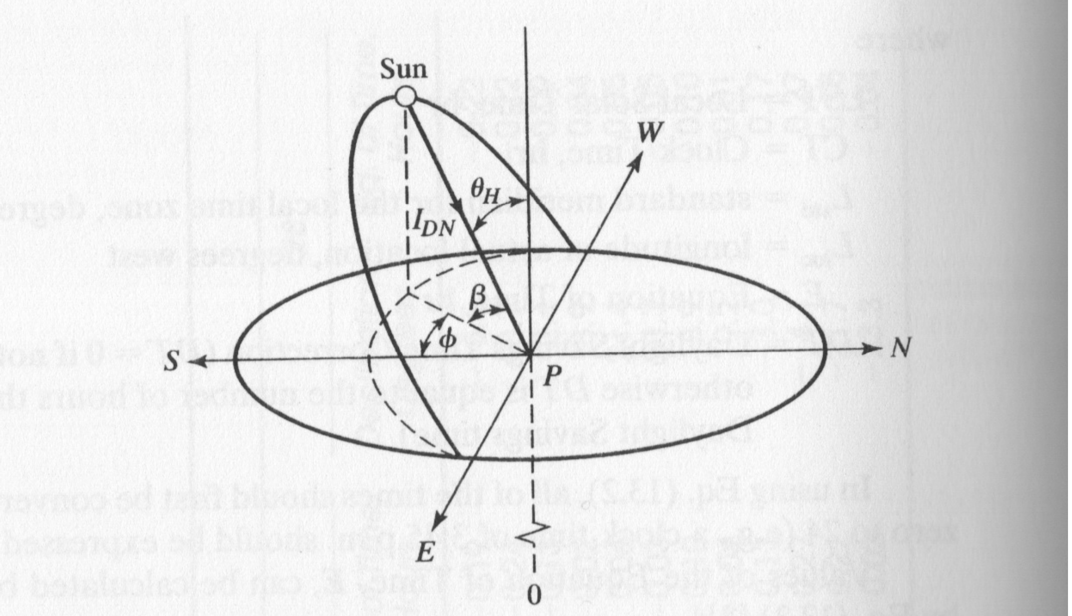


Figure 13.6 Definition of sun's zenith, altitude, and azimuth angles

<u>Three important angles (°)</u>

θ_H = sun's zenith angle
angle between the sun's rays and the local vertical

β = altitude angle
angle in a vertical plane between the sun's rays and the projection of the earth's horizontal plane

ϕ = solar azimuth angle
angle in the horizontal plane measured from south to the horizontal projection of the sun's rays

*Note that I_{DN} represents the sun's rays

Earth-sun relationships

- Relationships between l, h, d, and θ_H, β, and ϕ can all be described in this figure:

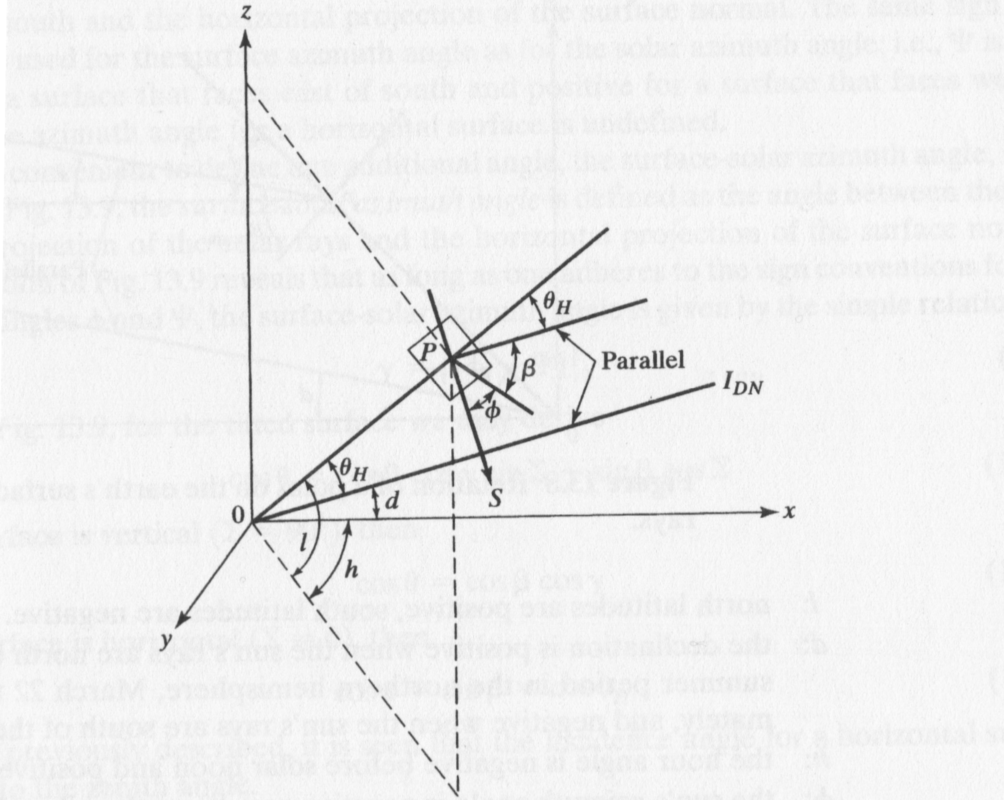


Figure 13.7 Relation of a point on the earth's surface to sun's rays.

Don't worry if this doesn't all make sense; there are formulas!

Determining solar angles

- After a lot of complex geometry/trigonometry…

$$\cos \theta_H = \cos l \cos h \cos d + \sin l \sin d$$

$$\sin \beta = \cos l \cos h \cos d + \sin l \sin d$$

$$\cos \phi = (\cos d \sin l \cos h - \sin d \cos l) / \cos \beta$$

A note on sign conventions for all of these relationships:
North latitudes (l) are positive, south latitudes are negative
Declination (d) is positive when sun's rays are north of equator
Hour angle (h) is negative before solar noon, positive after
Azimuth angle (ϕ) is negative before solar noon, positive after (same as h)

Note that β for solar noon = 90 degrees - | l - d |
Also note that $\beta + \theta_H$ = 90 degrees

**Keep units consistent

Earth-sun relationships

- Last but not least…
- The previous relationships identify a point on the earth's surface in relation to the sun
  - All valid for horizontal surfaces
  - Buildings are not horizontal surfaces!
- Need to describe surface-sun relationships:

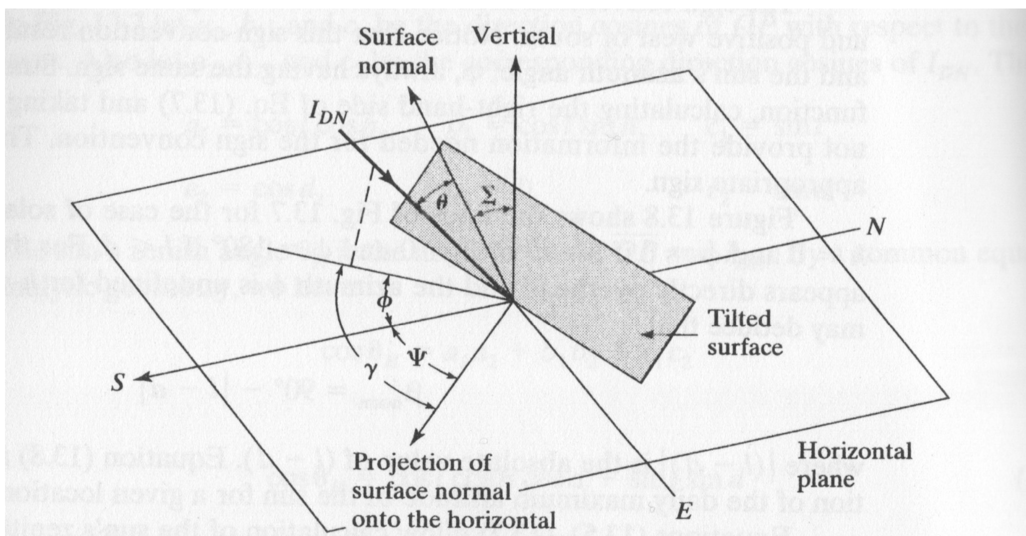


Figure 13.9 Definitions of surface azimuth, surface tilt, and surface-solar azimuth angles and the relation of sun's rays to a tilted surface.

Surface-sun relationships

<u>More important angles (°)</u>

θ = incidence angle
angle between the solar rays and the surface normal

Σ = surface tilt angle
angle between surface normal and the vertical
Vertical surface: Σ = 90°
Horizontal surface: Σ = 0°

Ψ = surface azimuth angle
angle between south and the horizontal projection of the surface normal

γ = surface-solar azimuth angle
angle between horizontal projection of solar rays and the horizontal projection of the surface normal

$\gamma = | \phi - \Psi |$

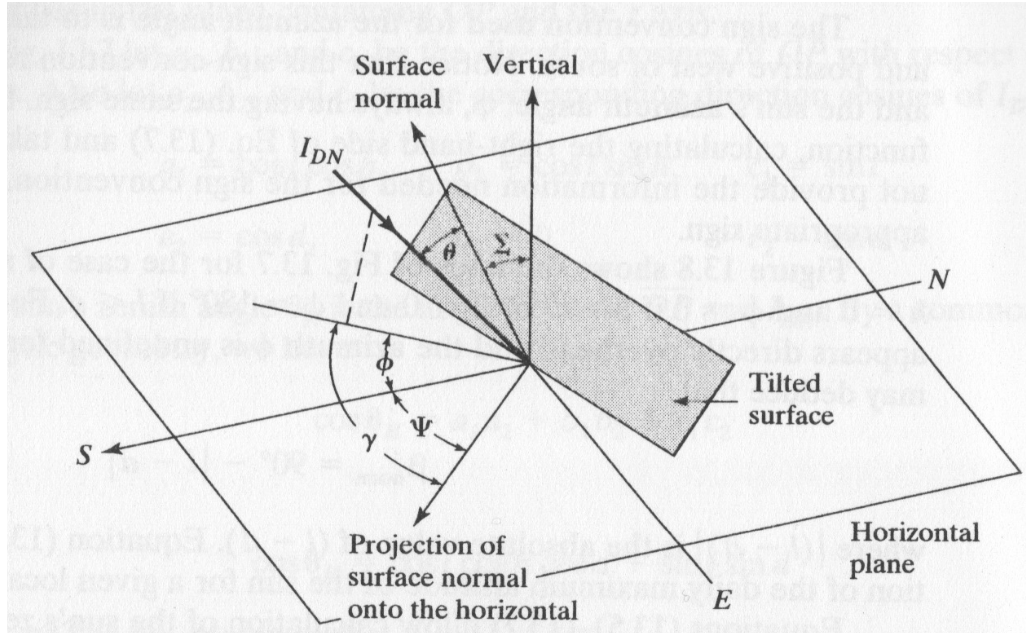


Figure 13.9 Definitions of surface azimuth, surface tilt, and surface-solar azimuth angles and the relation of sun's rays to a tilted surface.

*Sign convention: Ψ is negative for a surface that faces east of south and positive for a surface that faces west of south

Tilted surface:

$\cos\theta = \cos\beta \cos\gamma \sin\Sigma + \sin\beta \cos\Sigma$

Vertical surface (Σ = 90°):

$\cos\theta = \cos\beta \cos\gamma$

Surface-sun relationships: Example problem

- Calculate the sun's altitude (β) and azimuth (ϕ) angles at 7:30 am local solar time (LST) on August 7 for a location at 40 degrees north latitude

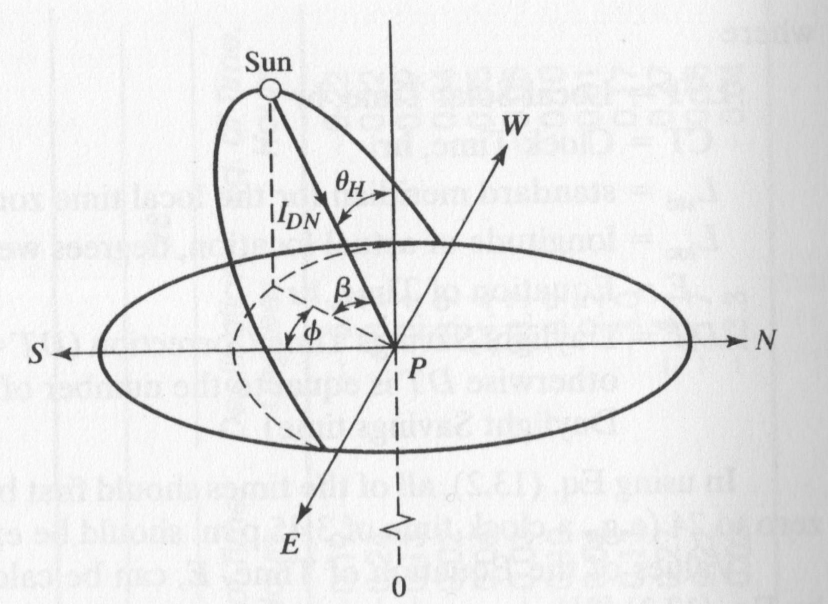


Figure 13.6 Definition of sun's zenith, altitude, and azimuth angles.

Surface-sun relationships: Example problem

- Calculate sun's incidence angle for a vertical surface that faces 25 degrees east of south and has a tilt angle of 60 degrees at 3:00 pm local solar time on June 7 for a location at 36 degrees north latitude

Translation:

Find θ

Given:

Ψ, Σ, l, h, β, ϕ

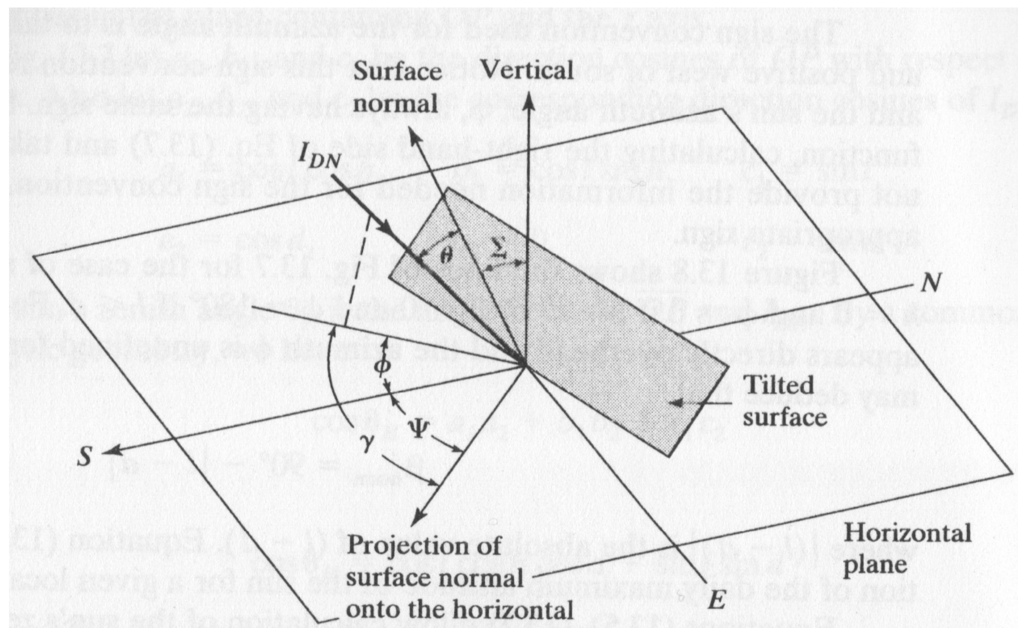


Figure 13.9 Definitions of surface azimuth, surface tilt, and surface-solar azimuth angles and the relation of sun's rays to a tilted surface.

What is this all about? … <u>Solar flux</u>

- Once we know earth-surface-sun relationships, we can eventually get to the effects of those relationships on actual solar radiation intensity

- Solar radiation intensity is roughly constant at the outer layer of the atmosphere
  - 1367 W/m^2 – varying a few percent depending on time of year

- The earth's atmosphere depletes some direct solar radiation
  - Intercepted by other air molecules, water molecules, dust particles
  - Remaining reaches earth's surface unchanged in wavelength
    - Direct radiation
  - The deflected radiation turns aside from the direct beam
    - Diffuse radiation

Estimating solar flux

- Estimating intensity of direct normal solar radiation:
  - There are many, *many* ways to estimate this
  - ASHRAE uses a model for “average clear days” that works well for most of our purposes

$$I_{DN} = Ae^{-B/\sin\beta}$$

Where:
I_{DN} = direct normal irradiance, or amount of solar radiation per unit area on a surface that is always held perpendicular to the sun’s rays (W/m^2)
A = apparent direct normal solar flux at outer edge of earth’s atmosphere (W/m^2)
B = empirically determined atmospheric extinction coefficient (dimensionless)
β = altitude angle

- Estimating intensity of diffuse horizontal radiation: $I_{dH} = CI_{DN}$

Where:
I_{dH} = diffuse horizontal irradiance, or that which is scattered (W/m^2)
C = empirically determined coefficient for typical “clear days” (dimensionless)

Typical clear day values for solar radiation

TABLE 13.3 Coefficients for Average Clear Day Solar Radiation Calculations for the Twenty-First Day of Each Month, Base Year 1964

	A		B	C		
	$\frac{\text{Btu}}{\text{hr}\cdot\text{ft}^2}$	$\frac{\text{W}}{\text{m}^2}$	*Dimensionless Ratios*		*Declination, deg*	*Equation of Time, hr*
January	390	1230	0.142	0.058	−20.0	−0.19
February	385	1215	0.144	0.060	−10.8	−0.23
March	376	1186	0.156	0.071	0.0	−0.13
April	360	1136	0.180	0.097	11.6	0.02
May	350	1104	0.196	0.121	20.0	0.06
June	345	1088	0.205	0.134	23.45	−0.02
July	344	1085	0.207	0.136	20.6	−0.10
August	351	1107	0.201	0.122	12.3	−0.04
September	365	1151	0.177	0.092	0	0.13
October	378	1192	0.160	0.073	−10.5	0.26
November	387	1221	0.149	0.063	−19.8	0.23
December	391	1233	0.142	0.057	−23.45	0.03

SOURCE: Adapted by permission from *ASHRAE Handbook, Fundamentals Edition*, 1993.

$$I_{DN} = Ae^{-B/\sin\beta}$$

Solar flux to building surfaces (finally!)

- Solar radiation striking a surface: $I_{solar} = I_D + I_d + I_R$
  - Direct + diffuse + reflected

- Direct (I_D): $I_D = I_{DN} \cos\theta$

Where:
θ = incidence angle, or the angle between the solar rays and the surface normal
I_{DN} = direct normal irradiance (W/m^2)

- Diffuse (I_d): $I_d = I_{dH} \dfrac{1+\cos\Sigma}{2}$

Where:
Σ = surface tilt angle, or the angle between surface normal and surface vertical
I_{dH} = diffuse horizontal solar radiation (W/m^2)

Solar flux to building surfaces (finally!)

- Reflected (I_R)
  - Radiation striking a surface after reflecting off surrounding surfaces
  - Similar to diffuse
  - Usually concerned with reflection from the ground

$$I_R = \frac{\rho_g I_H (1 - \cos\Sigma)}{2}$$

Where:
ρ_g = solar reflectance of the ground (depends on surface, usually 0.1-0.4)
I_H = total solar flux striking the horizontal ground (W/m^2)

$$I_H = I_{DN} \cos\theta_H + I_{dH}$$

Solar flux to building surfaces

- Reflected (I_R)
  - Values of reflectance (ρ_g) for common ground surfaces

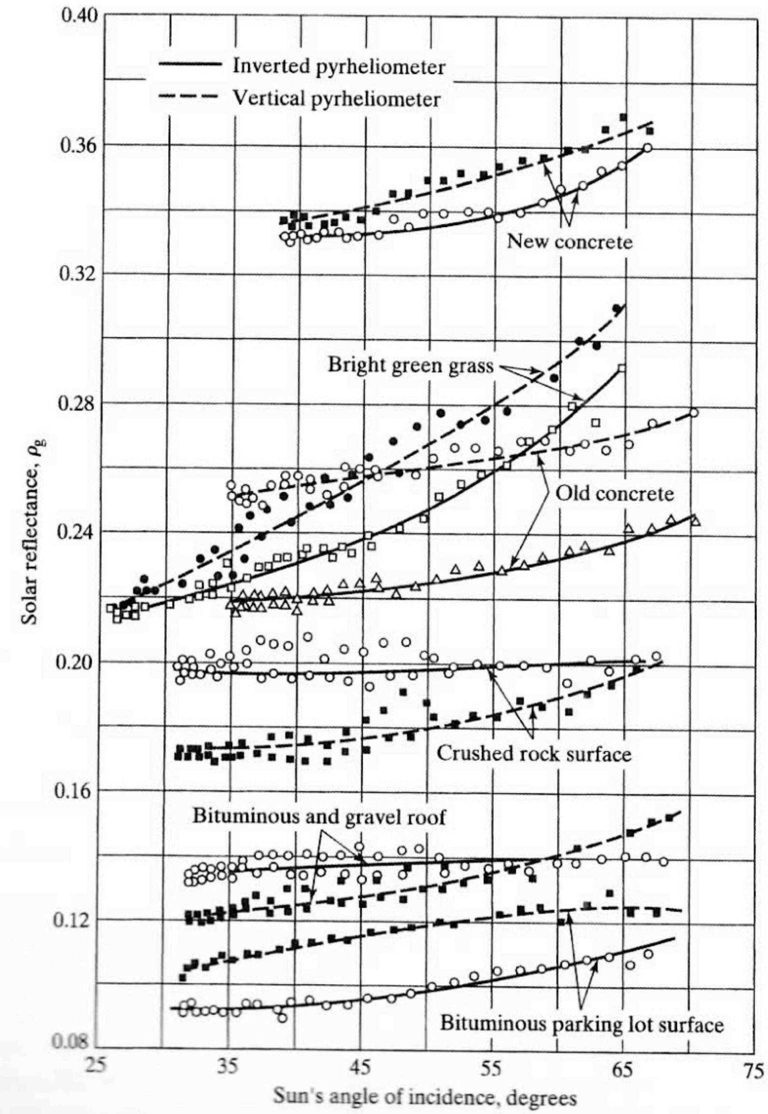


Figure 13.21 Solar reflectance for various ground surfaces. [Reprinted by permission from *ASHRAE Trans.*, 69 (1963), 31.]

Solar flux to building surfaces: Example problem

- Find the solar flux incident on the tilted surface used in the previous problem
  - Assume a ground reflectance of 0.15

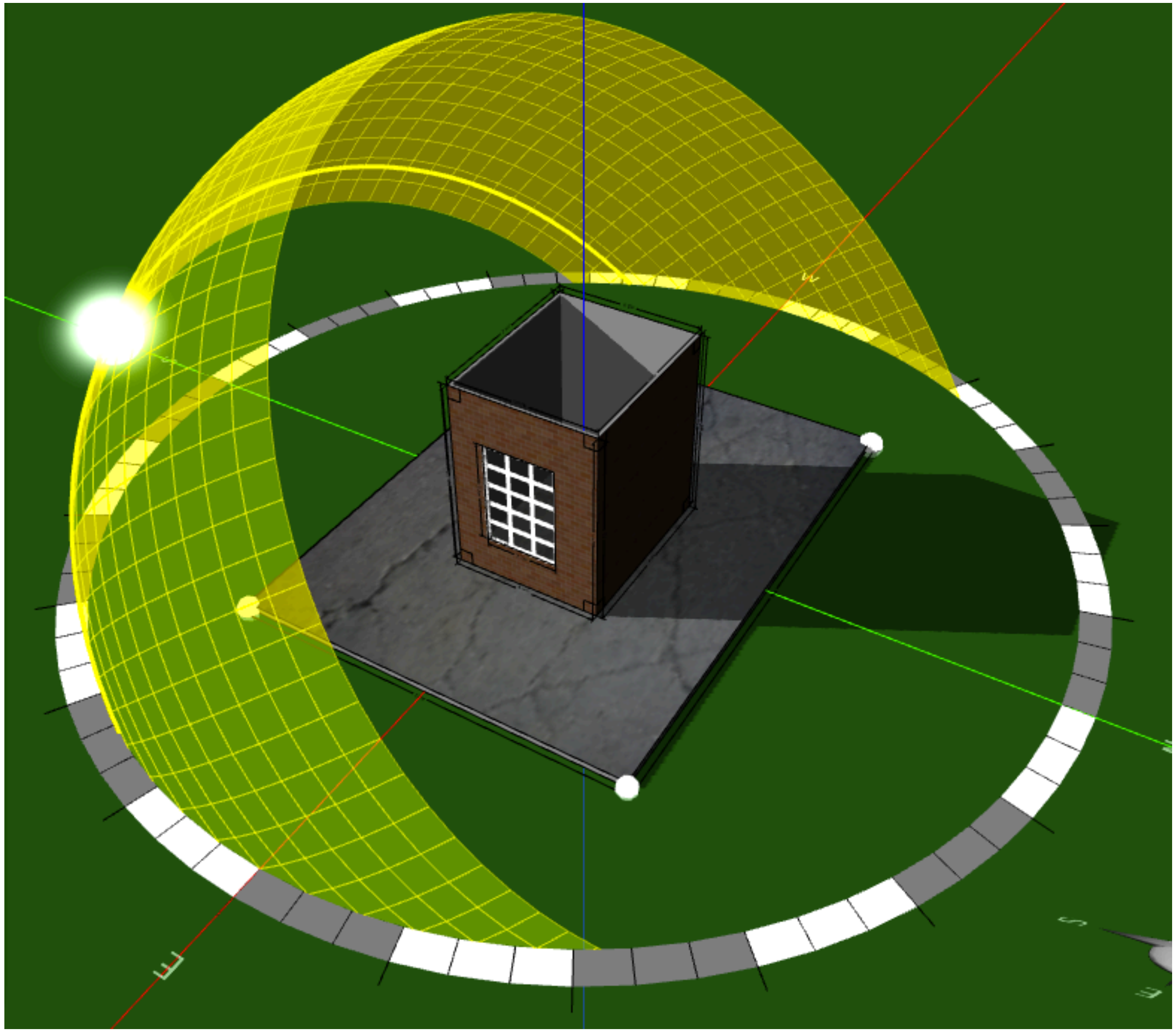
Solar orientation videos/software

- http://built-envi.com/wp-content/uploads/2013/07/solar_position_ies.zip
  - 56 mb zip file of several videos

- January, April, July, November 1st
  - Just one day (24 hours)

- 6 am, 9 am, 12 pm, and 4pm for an entire year

Solar orientation videos/software



http://energy.concord.org/energy3d/

The Concord Consortium

Refined solar data

- Now, you could make all of these calculations by hand for every hour of the day, or…

Downloading solar data

- For hourly sun positions, you can build a calculator or use one from the internet
  - http://www.susdesign.com/sunposition/index.php
  - http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html

- For solar position and intensity (from time and place)
  - http://www.nrel.gov/midc/solpos/solpos.html
  - Output of interest = “global irradiance on a tilted surface”

- For *actual* hourly solar data (direct + diffuse in W/m^2)
  - http://rredc.nrel.gov/solar/old_data/nsrdb/
  - Output of interest = “direct normal radiation” → adjust using $\cos\theta$
    - Note: “typical meteorological years”

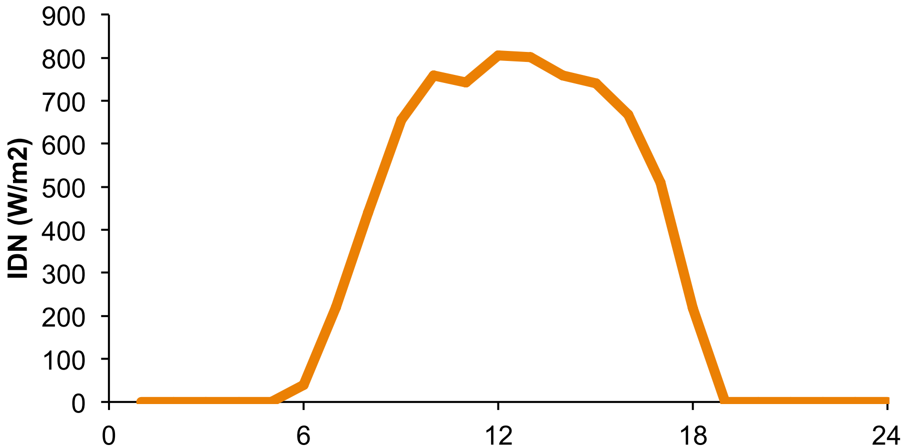
Typical meteorological year (TMY)

- For heating and cooling load calculations and for hourly building energy simulations, we often rely on a collection of weather data for a specific location
- We generate this data to be representative of more than just the previous year
  - Represents a wide range of weather phenomena for our location
  - TMY3: Data for 1020 locations from 1960 to 2005
    - Composed of 12 typical meteorological months
    - Each month is pulled from a random year in the range
    - Actual time-series climate data
    - Mixture of measured and modeled solar values
    - http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/
  - Variables include: outdoor temperature, direct normal radiation, wind speed, wind direction, outdoor RH, cloud cover, and more

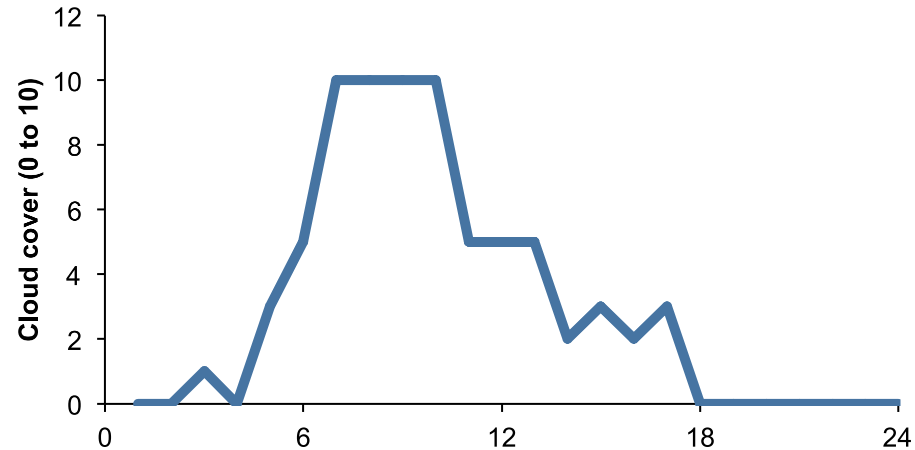
Typical meteorological year (TMY): Solar data

<u>Data for typical September 10th at Midway, Chicago, IL</u>

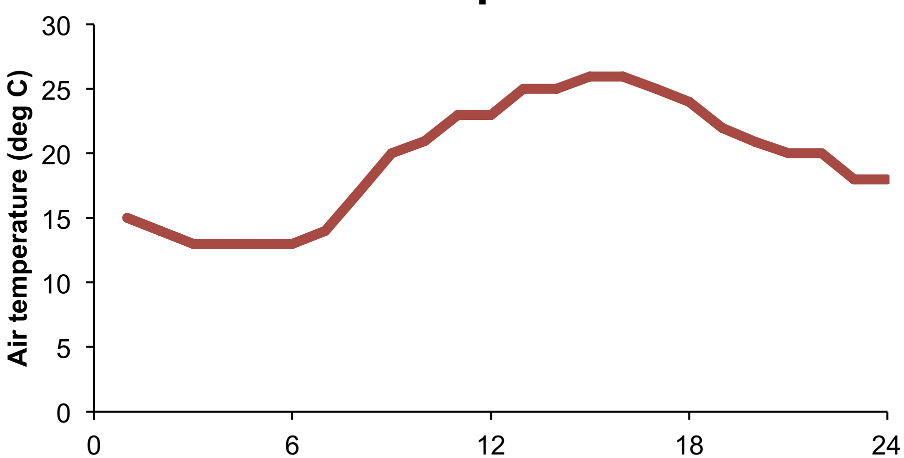
Direct Normal Irradiance



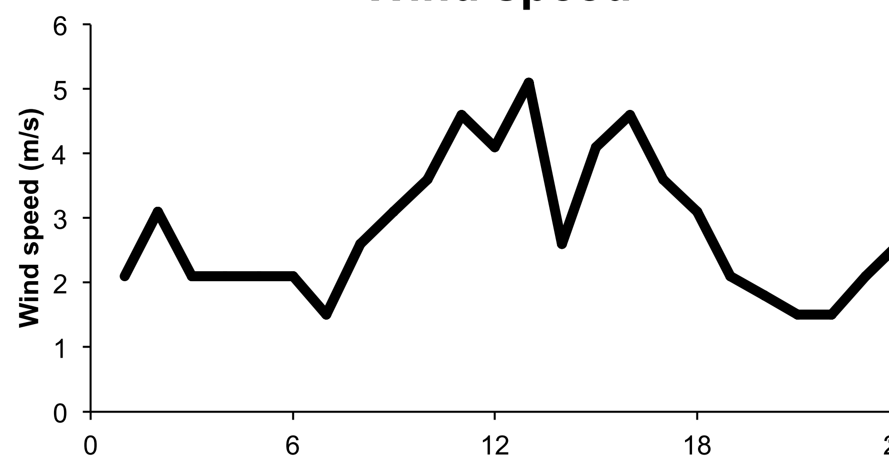
Cloud Cover



Air temperature

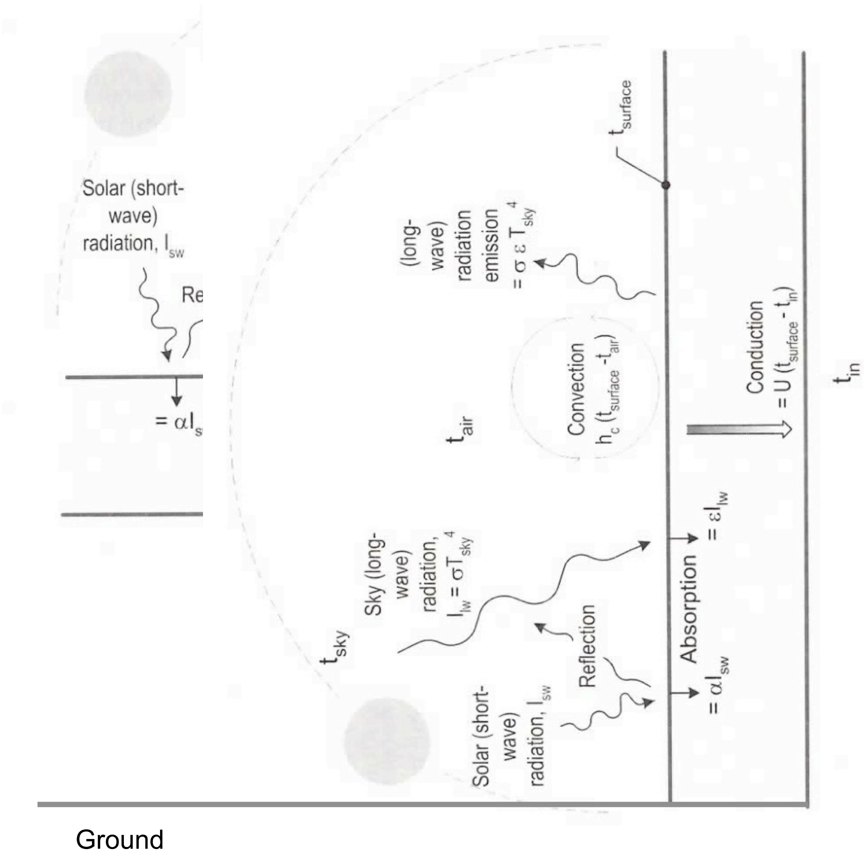


Wind speed



Bringing all the modes together (again)

- Back to our energy balance for a vertical surface:



$$q_{solar} + q_{lwr} + q_{conv} - q_{cond} = 0$$

$$\begin{aligned}
&\alpha I_{solar} \\
&+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surf}^4) \\
&+\varepsilon_{surface}\sigma F_{air}(T_{air}^4 - T_{surface}^4) \\
&+\varepsilon_{surface}\sigma F_{ground}(T_{air}^4 - T_{ground}^4) \\
&+h_{conv}(T_{air} - T_{surface}) \\
&-U(T_{surface} - T_{surface,interior}) = 0
\end{aligned}$$

We need to understand conduction through enclosures that are more complex than just single materials

Next lectures

- The next 2 lectures are on more complex conduction than we've previously dealt with
  - Realistic layers and assemblies
  - 2D and 3D conduction
  - Thermal bridges

- Tuesday Feb 9 will be a short class (only 1 hour)
  - NAS meeting travel