CHAMPS Workshop
Syracuse, September 9-11, 2009

Review of Solar Radiation Models

John Grunewald
**Available Models**

4 models are reviewed:

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Sky</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Alf Perschk implemented his PhD-model in ITT-TRNSYS</td>
<td>Measured / Generated</td>
<td>Real</td>
</tr>
<tr>
<td>2.</td>
<td>Andreas Nicolai implemented Petzold's model in the ThermalRoomModel</td>
<td>Measured</td>
<td>Real</td>
</tr>
<tr>
<td>3.</td>
<td>Claudia Finkenstein &amp; Heiko Fechner implemented Petzold/Häupl’s model in Delphin4, John implemented it in Delphin5</td>
<td>Measured</td>
<td>Real</td>
</tr>
<tr>
<td>4.</td>
<td>Kelvin Feng implemented a model based on ASHRAE Handbook and other sources in CHAMPS-Multizone</td>
<td>Generated</td>
<td>Clear</td>
</tr>
</tbody>
</table>
Radiation components in detail

Diffuse radiation
Direct sun radiation
Adsorption, Dispersion (Extinction)
Ozone, Carbon dioxide, Water vapor

Temperature
Relative humidity
Rain
Short wave radiation
(Visible + invisible, 0.2 .. 3 μm)
Long wave radiation
(Invisible, 3 .. 30 μm)
Wind velocity
Wind direction
Cloudiness
Air pressure
Atmospheric counter radiation
Diffuse radiation
Long wave emission
Direct and diffuse reflection
Radiation components in detail (short wave)

Surface of the sun
- Emission of radiative energy by the sun (nuclear fusion)

Top of the atmosphere
- Solar constant
  ~ eclipical length of the sun (season)

Bottom of the atmosphere
- Direct normal radiation and diffuse radiation
  ~ solar altitude (latitude)
  ~ solar azimuth (season, longitude, time zone)
  ~ extinction (elevation, solar altitude)
  ~ opaqueness (cloudiness, humidity, air pollution)

Building surface
- Direct radiation and diffuse radiation
  ~ inclination and orientation of the surface
  ~ albedo (diffuse reflection)
# Approaches to model short wave radiation on building surface

<table>
<thead>
<tr>
<th>Generated radiation</th>
<th>Measured radiation</th>
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<tr>
<td>1. Calculate solar constant, solar altitude</td>
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<td>13. Get total short wave radiation on building surface</td>
<td>13. -</td>
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</table>
Solar constant

Ecliptical length = Angle between current position and spring begin

Distance between sun – earth changes with time

ASHRAE table 7, pp. 31.14
Alf (corrected)
Kelvin
Alf
Equation of time and apparent solar time

Shift between apparent solar time and mean time due to:
• equation of time
• longitude
• time zone

Velocity of circulation changes with season

![Diagram of Earth and Sun showing Earth's orbit and equator]

- Alf
  Duffie and Beckman, Solar Engineering of Thermal Processes, 1980

- ASHRAE table 7, pp. 31.14

- Kelvin
Equation of time and apparent solar time

**Alf**

- Longitude in °: \( \xi = -82.533 \)
- Time zone: \( t_z = -5 \)
- Eastern standard time offset

\[
\tau(\varphi h, rs) := \varphi h + ET_1(rs) + \frac{1}{15}(\xi - t_z) \quad \text{in h}
\]

- Mean time
- Time shift
- Longitude
- Time zone

\[
\text{corr: } \tau(\varphi h, rs) := \text{wenn}(\tau(\varphi h, rs) < 0, \tau(\varphi h, rs) + 24, \tau(\varphi h, rs))
\]

**Kelvin**

- \( + \)
- \text{conf. ASHRAE eqn. 10, pp. 31.13}

\[
\begin{align*}
\text{LSM} := -15 \cdot t_z & \quad \text{LSM} = 75 \\
\text{LON} := -\xi & \quad \text{LON} = 82.533
\end{align*}
\]

- Local standard time meridian in °
- Local longitude in °

\[
\text{AST}(\varphi h, rs) := \varphi h + \frac{\text{ET}_4(rs)}{60} + \frac{\text{LSM} - \text{LON}}{15} \quad \text{in min}
\]

\[
\text{corr: } \text{AST}(\varphi h, rs) := \text{wenn}(\text{AST}(\varphi h, rs) < 0, \text{AST}(\varphi h, rs) + 24, \text{AST}(\varphi h, rs))
\]
Hour angle

The earth rotates 15° in 1 hour apparent solar time.

ASHRAE equ. 13, pp. 31.15
Solar declination

Slope of the equatorial plane changes with time (relatively to the earth orbit plane)

\[
\delta_{1}(\tau s) = 0.395 - 23.256 \cdot \cos\left(2 \cdot \frac{\tau s}{365} + 9.053\right) - 0.392 \cdot \cos\left(4 \cdot \frac{\tau s}{365} + 5.329\right) - 0.176 \cdot \cos\left(6 \cdot \frac{\tau s}{365} - 10.084\right)
\]

**Alf**

\[
\delta_{2}(\tau s) = -23.256 \cdot \cos\left(360 \cdot \frac{\tau s + 10}{365}\right)
\]

**Andreas**

**Claudia**

\[
\Phi_{12_{365}} := \frac{2 \cdot \pi}{365} \quad K11 := 10 + \frac{365}{4} \quad \Pi_{180} := \frac{\pi}{180} - 23.5 \quad \Pi_{2} := 2 \cdot \pi
\]

\[
\phi := \frac{\pi}{180} \quad \sin(\phi) := \sin(\Phi) \quad \cos(\phi) := \cos(\Phi)
\]

\[
del(t) = -23.5 \cdot \sin\left(\frac{2 \cdot \pi}{365} \left[ t + \left(10 + \frac{365}{4}\right)\right] \right) \cdot \frac{\pi}{180}
\]

\[
\delta_{3}(t) := \arcsin(del(t))
\]
Solar declination

Slope of the equatorial plane changes with time (relatively to the earth orbit plane)

Kelvin


\[ n_{\text{deg}}(\tau s) := 360 - \frac{\tau s - 1}{365} \]
\[ \text{dtr} := \frac{\pi}{180} \]
\[ n_r(\tau s) := n_{\text{deg}}(\tau s) \cdot \text{dtr} \]
\[ \text{cn}(\tau s) := \cos(n_r(\tau s)) \]
\[ \text{sn}(\tau s) := \sin(n_r(\tau s)) \]
\[ \text{c2n}(\tau s) := \cos(2n_r(\tau s)) \]
\[ \text{s2n}(\tau s) := \sin(2n_r(\tau s)) \]
\[ \text{c3n}(\tau s) := \cos(3n_r(\tau s)) \]
\[ \text{s3n}(\tau s) := \sin(3n_r(\tau s)) \]

\[ \delta_4(\tau s) := (0.3963723 - 22.9132745 \cdot \text{cn}(\tau s) + 40154304 \cdot \text{sn}(\tau s) - 0.3873205 \cdot \text{c2n}(\tau s) + 0.05196728 \cdot \text{s2n}(\tau s) - 0.1545267 \cdot \text{c3n}(\tau s) + 0.0847977 \cdot \text{s3n}(\tau s)) \]

ASHRAE eq. 11, pp. 31.13

\[ \delta_{\text{ASH}}(\tau s) = 23.45 \cdot \sin\left(360 \cdot \frac{\tau s + 284}{365}\right) \]

John Grunewald

Syracuse CHAMPS Workshop 2009: Review of Solar Radiation Models
Solar declination

Slope of the equatorial plane changes with time (relatively to the earth orbit plane)

1 Alf
2 Andreas
3 Claudia
4 Kelvin
ASHRAE
Equatorial and horizontal systems

**Equatorial system**
- Hour angle $\gamma_h$ (linear with solar time)
- Solar declination $\delta$ ($-23^\circ$ ... $+23^\circ$)

**Horizontal system**
- Solar azimuth $a$
- Solar altitude $h$
Solar altitude

\[ \text{Alf} \]
\[
\sin h_1(\tau h, rs) = \sin G(\phi) \cdot \sin G(\delta_1(rs)) - \cos G(\phi) \cdot \cos G(\delta_1(rs)) \cdot \cos G(\gamma h(\tau h, rs))
\]
\[
h_1(\tau h, rs) = \arcsin(\sin h_1(\tau h, rs))
\]

\[ \text{Andreas} \]
\[
\sin h_2(t) = \sin G(\phi) \cdot \sin G(\delta_2(t)) - \cos G(\phi) \cdot \cos G(\delta_2(t)) \cdot \cos G\left(360 \cdot \frac{\tau h(t)}{24}\right)
\]
\[
h_2(t) = \arcsin(\sin h_2(t))
\]

\[ \text{Claudia} \]
\[
\sin h_3(t) = \sin(\Phi h) \cdot \sin[Fakt 1 \cdot \sin[\Pi 2_{360t} + K1]] \cdot \Pi_1 180] - \cos(\Phi h) \cdot \cos[Fakt 1 \cdot \sin[\Pi 2_{360t} + K1]] \cdot \Pi_1 180] \cdot \cos(\Pi 2 t)
\]
\[
h_3(t) = \arcsin(\sin h_3(t))
\]

\[ \text{Kelvin} \quad \text{conf. ASHRAE equ. 14, pp. 31.16} \]
\[
\sin h_4(t) = \cos G(\phi) \cdot \cos G(\delta_4(t)) \cdot \cos G(H(\tau h(t), rs t(t))) + \sin G(\phi) \cdot \sin G(\delta_4(t))
\]
\[
h_4(t) = \arcsin(\sin h_4(t))
\]
Solar altitude

Winter

Summer

1 Alf
2 Andreas
3 Claudia
4 Kelvin
Solar azimuth

**Alf**

\[
a_1(\tau h, rs) = \cos\left(\frac{\sin h_1(\tau h, rs) \cdot \sin G(\phi) - \sin G(\delta_1(rs))}{\cos G(h_1(\tau h, rs)) \cdot \cos G(\phi)}\right)
\]

**corrected**  
\[a_1(\tau h, rs) = \text{wenn}(\text{y}(\tau h, rs) > 180, 180 + a_1(\tau h, rs), 180 - a_1(\tau h, rs))\]

\[
\sin a_1(\tau h, rs) = \sin G(a_1(\tau h, rs))
\]

**Andreas**

**corrected**  
\[t_{sh} = 182\]

\[
x_2(t) = \sin G(\phi) \cdot \cos G\left(360 \cdot \frac{\tau h_{t}t + tsh}{24}\right) \cdot \cos G(\delta_2(1 + tsh)) - \sin G(\delta_2(1 + tsh)) \cdot \cos G(\phi)
\]

\[
y_2(t) = \sin G\left(360 \cdot \frac{\tau h_{t}t + tsh}{24}\right) \cdot \cos G(\delta_2(1 + tsh))
\]

\[a_2(t) = \text{wenn}(\text{atan2G}(x_2(t), y_2(t)) < 0, \text{atan2G}(x_2(t), y_2(t)) + 360, \text{atan2G}(x_2(t), y_2(t)))\]

\[
\sin a_2(t) = \sin G(a_2(t))
\]

**Claudia**

\[\cos h_3(t) = \sqrt{1 - \sin h_3(t)^2}\]

\[
\sin a_3(t) = \frac{\cos[\text{Fakt1} \sin[\text{Pi2} 265 (t + \text{K1})] \text{Pi180}] \sin(\text{Pi2} t)}{\cos h_3(t)}
\]

**Kelvin**

**conf. ASHRAE equ. 15, pp. 31.15**

\[\cos h_4(t) = \cos(\text{asin}(\sin h_4(t)))\]

\[
a_4(t) = \cos G\left(\frac{\sin h_4(t) \cdot \sin G(\phi) - \sin G(\delta_4(t))}{\cos h_4(t) \cdot \cos G(\phi)}\right) \cdot H(\tau h_{t}t(t), rs_{t}(t))
\]

\[\sin a_4(t) = \sin G(a_4(t))\]

**John Grunewald**

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Solar azimuth

1 Alf
2 Andreas
3 Claudia
4 Kelvin
Extinction in dry and clean atmosphere

Geographical data of location

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitude in ° (Tampa)</td>
<td>ξ := -82.5333</td>
</tr>
<tr>
<td>Time zone in h (Miami)</td>
<td>tz := -5</td>
</tr>
<tr>
<td>Latitude in ° (Tampa)</td>
<td>φ := 27</td>
</tr>
<tr>
<td>Elevation in m (Tampa)</td>
<td>Hsee := 3</td>
</tr>
</tbody>
</table>

Ozon, Carbon Dioxide, Oxygen

Hsee = 0

Dimensionless thickness parameter of atmosphere as function of elevation and solar altitude

\[
G(\theta_h, \tau_s) = \frac{9.381 \left( \sin_h(\tau_s) + \sqrt{1.04 \times 10^{-4} + \sin_h(\tau_s)^2} \right)}{2002 \left( 1 - Hsee \times 10^{-4} \right)} + 0.912
\]

Normalized fraction of solar irradiation arriving on the ground

\[
q_{n\_clear}(\theta_h, \tau_s) = \begin{cases} 0 & \sin_h(\tau_s) \geq 0, \exp \left( \frac{1}{Q(\theta_h, \tau_s)} \right) > 0 \\ 1 & \text{otherwise} \end{cases}
\]

![Graph showing the percentage of sun radiation arriving on the ground over time in hours for different months in Tampa, with clean/dry air depicted.]
Opaqueness of the atmosphere

Definition of opaqueness factor $T$

$q_{n,\text{clear}}$ normalized radiation fraction for clear sky

$q_{n,\text{real}} = q_{n,\text{clear}}^T$ normalized radiation fraction for real sky

Adapted mean opaqueness factor such that annual sum of measured and calculated direct radiation energy matches.

Mean opaqueness factor for Tampa $T \approx 7.9$

For example:

$T = 3$ means

1 real atmosphere has same extinction as 3 clean/dry atmospheres

Solar constant

Direct normal radiation clear sky

Direct normal radiation real sky

Direct horizontal radiation
Matching the opaqueness factor

\[
\text{Mean}_\text{Dir}_\text{Meas} := \left( \sum_i q_{\text{dir}}\text{Meas}_i \right) \times 10^{-3}
\]
\[
\text{Mean}_\text{Dir}_\text{Calc} = \left( \sum_i q_{\text{dir\_hor\_tdata}_i} \right) \times 10^{-3}
\]

\[
\text{Mean}_\text{Dir}_\text{Meas} = 1.074 \times 10^3 \quad \text{Mean}_\text{Dir}_\text{Calc} = 1.097 \times 10^3
\]
in kWh/m²

Comparison of measured and generated radiation on horizontal surface
Comparison with ASHRAE

ASHRAE Tab 7, pp 31.14, eq 20 pp 31.16

\[ E_{DN}(t) = \text{wenn} \left( \frac{A_{ASH}(t)}{E_{ASH}(t)} \right) > 0, \quad \frac{A_{ASH}(t)}{E_{ASH}(t)} \exp \left( \frac{B_{ASH}(t)}{\sin h_4(t)} \right) \]

Representative of conditions on cloudless days for a relatively dry and clean atmosphere

\[ E_{DN_{15}}(t) = 1.15 \cdot E_{DN}(t) \]

Maximum can be up to 15% higher

*Difference in summer time even larger.

**Alf:**
- Solar constant
- Direct normal radiation clear sky*
- Direct normal radiation real sky
- Direct horizontal radiation

**ASHRAE:**
- Solar constant
- Direct normal radiation clear sky*
- Direct normal radiation real sky +15%
Approaches to model short wave radiation on building surface

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<td></td>
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</table>
Solar angle relations

Horizontal and vertical components

\[ q_{\text{dir}, H} = q_{\text{dir}, N} \cdot \sin(h) \]

\[ q_{\text{dir}, V} = q_{\text{dir}, N} \cdot \cos(h) = \frac{1}{\tan(h)} \cdot q_{\text{dir}, H} \]
Solar angle relations

Horizontal and vertical components

\[ q_{\text{dir}, H} = q_{\text{dir}, N} \cdot \sin(h) \]
\[ q_{\text{dir}, V} = q_{\text{dir}, N} \cdot \cos(h) = \frac{1}{\tan(h)} \cdot q_{\text{dir}, H} \]

Wall orientation

- \( a \) (solar azimuth)
- \( \beta \) (facade azimuth)

\[ q_{\text{dir}, \beta} = \cos(a - \beta) \cdot q_{\text{dir}, V} = \frac{\cos(a - \beta)}{\tan(h)} \cdot q_{\text{dir}, H} \]

Limit this ratio to values < 10!
Solar angle relations

Horizontal and vertical components

\[ q_{\text{dir},H} = q_{\text{dir},N} \cdot \sin(h) \]
\[ q_{\text{dir},V} = q_{\text{dir},N} \cdot \cos(h) = \frac{1}{\tan(h)} \cdot q_{\text{dir},H} \]

Wall orientation

- \( \alpha \) (solar azimuth)
- \( \beta \) (facade azimuth)

Wall inclination

\[ q_{\text{dir},\beta} = \cos(a - \beta) \cdot q_{\text{dir},V} = \frac{\cos(a - \beta)}{\tan(h)} \cdot q_{\text{dir},H} \]

Limit this ratio to values < 10!

\[ q_{\text{dir},\alpha} = \sin(\alpha) \cdot q_{\text{dir},\beta} + \cos(\alpha) \cdot q_{\text{dir},H} \]

\[ = \left( \sin(\alpha) \cdot \frac{\cos(a - \beta)}{\tan(h)} + \cos(\alpha) \right) \cdot q_{\text{dir},H} \]
Direct sun radiation on different wall surfaces in **Tampa**

**Winter**

Daylight time

**Summer**

**Spring**

**Autumn**

<table>
<thead>
<tr>
<th>Time in h</th>
<th>H</th>
<th>E</th>
<th>N</th>
<th>S</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
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<tr>
<td>8</td>
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<tr>
<td>12</td>
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<td>16</td>
<td></td>
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<tr>
<td>20</td>
<td></td>
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<tr>
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<td></td>
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**Direct radiation in W/m²**
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Diffuse radiation ratio

\[ q_{\text{diff.,H}} = X \cdot (S - q_{\text{dir.,N}}) \cdot \sin(h) \]

Direct radiation that gets absorbed or reflected in (by) the atmosphere

Ratio of diffuse radiation that gets emitted to the ground

Ozone, Carbon dioxide, Water vapor

Direct sun radiation
Adsorption, Dispersion (Extinction)
Diffuse radiation
Direct and diffuse reflection
Matching the diffuse radiation ratio

Match the annually received energy per m²

\[ \text{Mean}_\text{Diff}_\text{Meas} = \left( \sum q_{\text{diff}_\text{Meas}} \right) \times 10^{-3} \quad \text{Mean}_\text{Diff}_\text{Calc} = \left( \sum q_{\text{diff}_\text{hor}(\text{data}_i)} \right) \times 10^{-3} \quad \rightarrow \quad X = 0.326 \]

\[ \text{Mean}_\text{Diff}_\text{Meas} = 717.095 \quad \text{Mean}_\text{Diff}_\text{Calc} = 717.166 \quad \text{in kWh/m}^2 \]

Comparison of measured and generated radiation on horizontal surface
Total diffuse radiation

**Diffuse radiation on wall surface**

Albedo $\rho_e = 0.2$  
Albedo = diffuse reflection coefficient of ambient ground

$$q_{\text{diff}}(\tau, \tau_s) = \begin{cases} \sin h_1(\tau, \tau_s) > 0 & \times (S_1(\tau_s) - q_{\text{dir}}(\tau, \tau_s)) \cdot \sin h_1(\tau, \tau_s), 0 \end{cases}$$

$$q_{\text{glob}}(\tau, \tau_s) := q_{\text{diff}}(\tau, \tau_s) + q_{\text{dir}}(\tau, \tau_s)$$

$$q_{\text{diff}}(\tau, \tau_s, \alpha) = \cos G \left( \frac{\alpha}{2} \right)^2 \cdot q_{\text{diff}}(\tau, \tau_s) + \sin G \left( \frac{\alpha}{2} \right)^2 \cdot q_{\text{glob}}(\tau, \tau_s) \cdot \rho_e$$

- Diffuse radiation from atmosphere
- Diffuse reflection from ground

Wall inclination $\alpha$

Direct and diffuse reflection  
Depends on albedo

---

John Grunewald  
Syracuse CHAMPS Workshop 2009: Review of Solar Radiation Models
Diffuse sun radiation on different wall surfaces

Winter

Summer

Spring

Autumn

Tampa

Diffuse radiation in W/m²

John Grunewald

Syracuse CHAMPS Workshop 2009: Review of Solar Radiation Models
Total sun radiation on vertical wall surfaces (Tampa)
Long wave radiation
Long wave atmospheric counter radiation

We know ...

Long wave atmospheric counter radiation is a temperature-depended self-radiation of
- atmosphere and clouds (emission of O_3, CO_2 and H_2O)
- surrounding buildings
- ground

Clear sky

\[ q_{\text{sky}} = (a - b \cdot 10^{-c \cdot x}) \cdot C_{\text{black}} \cdot (T/100)^4 \] \hspace{1cm} W/m^2 \hspace{1cm} Emission of the sky

\[ \varepsilon_{\text{sky}} = 0.75 \text{ (winter)} \ldots 0.8 \text{ (summer)} \] \hspace{1cm} Sky emission coefficient after BOLZ and FALKENBERG

Overcast sky

More clouds – more emission
Low clouds influence more that high clouds
Thick, dense clouds: \( \varepsilon_{\text{sky}} \to 1 \)

\[ \varepsilon_{\text{sky}} = f(\text{cl}) \] \hspace{1cm} Sky emission coefficient as function of cloudiness

\[ \text{cl} = 0 \ldots 1 \] \hspace{1cm} Cloudiness

How to generate long wave sky radiation data?
1. Idealize sky as a gray radiator

\[ q_{\text{sky}} = \varepsilon_{\text{sky}} (\text{cl}) \times C_{\text{black}} \times (T/100)^4 \]

with

\[ \varepsilon_{\text{sky}} (\text{cl}) = \varepsilon_{\min} + (\varepsilon_{\max} - \varepsilon_{\min}) \times \text{cl} \]

\[ T = \text{air temperature} \]

2. Then compare with data from a meteorological station ...
Long wave emission from ground: Essen Germany

1. Idealize ground as a gray radiator

\[ q_{\text{lw}} = -\varepsilon_{\text{lw}} \cdot C_{\text{black}} \cdot (T/100)^4 \]

with

\[ \varepsilon_{\text{lw}} = 0.9 \]

\[ T = \text{air temperature} \]

2. Then compare with data from a meteorological station ...

--- TRY Essen long wave emission data
--- calculated from TRY Essen air temperature
Model to handle radiation input to a building energy simulation code

Input:  

Minimum  
- Longitude, time zone, latitude, elevation  
- Opaqueness (literature values seem to be too low), diffuse ratio (not much known)  
- Cloudiness + Temperature

Better  
- Longitude, time zone, latitude, elevation  
- Direct and diffuse horizontal radiation  
- Cloudiness + Temperature (Delphin 5 / CHAMPS-BES can be simplified here)

Optimum  
- Longitude, time zone, latitude, elevation  
- Direct and diffuse horizontal radiation, time dependent shadowing effects  
- Atmospheric counter radiation

Params: Absorption and emission coeffs, albedo, surface temperature

Output: Short wave and long wave radiation balances on building surface
Review of Solar Radiation Models

John Grunewald