How sampling impacts the speed, accuracy, and interpretability of rendering with Radiance

Stephen Wasilewski
Outline

Part 1:
- The Dimensions of Daylight
- Sampling a Ray
  + the no ambient crache course
  + parameter testing

Part 2:
- Sampling a Point
- Sampling the Sky
  + time $\rightarrow$ angle
  + components
  + results
- Modeling Interlude
  + what do our results tell us?
- Sampling an Area

Part 3: Raytraverse
- Distribution
- Documentation
- The Command Line
the dimensions of daylight
The Daylight Simulation Process

Model

Sample → Render

view ray → (ir)radiance

Evaluate → Interpret

metric
Assumptions

Sample → Render → Evaluate → Interpret

Geometry, Material, Sky, Weather → Model

Extent, Resolution → Algorithm

Parameters → Criteria

Metric
Every Simulation based analysis begins with a sampling strategy about where to look
when to look
and what to look at
Because at useful resolutions the evaluation space is huge

point resolution: \((2\text{ft point grid})\) \(<\text{ieslm-83-12}>\)

\(\times\)

temporal resolution: \((\text{hours in TMY})\) \(<\text{inertia from energy modeling}>\)

\(\times\)

directional resolution: \(\frac{2\pi}{10^4} \text{ (point)}\) \(\text{OR} \frac{2\pi}{10^6} \text{ (image)}\)

primary rays/100 ft\(^2\): \(10^5\) \(\text{OR} \ 10^{11}\)
CBDM Methods for Visual Comfort: Illuminance ($E_v$) based

Sample → Render → Evaluate → Interpret

$A \cdot E_v + C$

$DGP = 5.87 \cdot 10^{-5} E_v + 9.18 \cdot 10^{-2} \log_{10}(1 + n \sum_{i=1}^{L_{2}} s,i \omega_{s,i} E_{1.87} v P_{2,i}) + 0.16$

$DGPs = 6.22 \cdot 10^{-5} E_v + 0.184$
CBDM Methods for Visual Comfort: phase-based

Sample Evaluate Interpret

transmission

sky

tregenza/reinhart

klems

indirect

Model

DGP = 5.87 \times 10^{-5} \ \text{E}_v + 9.18 \times 10^{-2} \ \log_{10} \left(1 + \sum_{i=1}^{n} L_{s,i} \omega_{s,i} E_1.87 v_{P2} \right)

DGPs = 6.22 \times 10^{-5} \ \text{E}_v + 0.184 A E_v + C

DGP = A E_v + B \ \log_{10} \left(\sum_{i=1}^{n} L_{s,i} \omega_{s,i} E_1.87 v_{P2} \right) + C

UGR, UGP = A \ \log_{10} \left(\sum_{i=1}^{n} L_{s,i} \omega_{s,i} E_4 L_{b,P2} \right)

A = \begin{bmatrix} a_1 & a_2 & \ldots \\ \vdots & \ddots & \vdots \\ a_t & \ddots & a_v \end{bmatrix}

B = \begin{bmatrix} b_1 & b_2 & \ldots \\ \vdots & \ddots & \vdots \\ b_t & \ddots & b_v \end{bmatrix}
CBDM Methods for Visual Comfort: eDGP

\[
\text{DGP} = A \cdot E_v + B \cdot \log_{10} \left( 1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{E_{1.87}^v P_i^2} \right) + C
\]
sampling a ray
No Cache

Ambient Calculation

Crash Course

John Mardaljevic

Professor of Building Daylight Modelling
School of Civil & Building Engineering
Loughborough University, UK
It is Every Ray for Itself

w/ cache

w/o cache
-lw behaves very differently

```
static int
amsample( /* initial ambient division sample */
    AMBHEMI *hp,
    int i,
    int j,
    int n
)

if (ambacc > FTINY)
    setcolor(col: ar.rcoef, AVGREFL, AVGREFL, AVGREFL);
else
    copycolor(c1: ar.rcoef, c2: hp->acoef);
if (rayorigin(&ar, AMBIENT, hp->rp, ar.rcoef) < 0)
    return(0);
if (ambacc > FTINY) {
    multcolor(c1: ar.rcoef, c2: hp->acoef);
    scalecolor(col: ar.rcoef, sf: 1./AVGREFL);
}
```

<table>
<thead>
<tr>
<th>w/ cache</th>
<th>w/o cache</th>
</tr>
</thead>
</table>

ambient divisions do not decay rayweight

ambient divisions do decay rayweight
so -ad does too

First Ambient Intersection:

Subsequent:

decays with reflectance to 49

w/ cache

w/o cache

< 1/ambdiv after first ambient bounce

equals 1

always true after first ambient bounce

up to the nearest square number to ambdiv

up to the nearest square number to ambdiv

1
Key Parameters with -aa 0

- **ad:** the only remaining resolution parameter

- **lr:** can be used instead of -ab to limit ray-depth. By setting negative avoids some bias from a hard cutoff

- **lw:** if this is too big, -ad and -lr will not behave intuitively. If it is too small time is wasted on very small contributions
Determining Settings: Image Based

benchmark: -ad 4000 -lw 1e-5 -lr -14
repeated 8 x 32 times samp/sec: 1.0
rRMSD: 0.012 rMsd: 0.000
changing -lw (increasing count for equal time)

- \texttt{-ad 4000 -lw 1e-6 -lr -14}
  repeated 1x32 times
  samp/sec: 3.7
  rRMSD: 0.032
  rMSD: -0.001

- \texttt{-ad 4000 -lw 1e-5 -lr -14}
  repeated 2x32 times
  samp/sec: 3.9
  rRMSD: 0.024
  rMSD: 0.000

- \texttt{-ad 4000 -lw 1e-4 -lr -14}
  repeated 5x32 times
  samp/sec: 3.9
  rRMSD: 0.034
  rMSD: 0.000
Reduce Oversampling

- \texttt{ad 4000 -lw 1e-5 -lr -14}
  repeated 4 x 32 times
  samp/sec: 1.8
  rRMSD: 0.017
  rMSD: 0.000

- \texttt{ad 4000 -lw 1e-5 -lr -14}
  repeated 2 x 32 times
  samp/sec: 3.9
  rRMSD: 0.024
  rMSD: 0.000

- \texttt{ad 4000 -lw 1e-5 -lr -14}
  repeated 1 x 32 times
  samp/sec: 8.5
  rRMSD: 0.035
  rMSD: 0.000
Reduce -ad (proportionally adjust -lw)

-\text{-ad} \, 1000 \, -\text{lw} \, 4e-5 \, -\text{lr} \, -14 \\
\text{repeated 32 times} \quad \text{samp/sec: 32.7} \\
r\text{RMSD: 0.072} \\
r\text{MSD: 0.000}

-\text{-ad} \, 500 \, -\text{lw} \, 8e-5 \, -\text{lr} \, -14 \\
\text{repeated 32 times} \quad \text{samp/sec: 66.1} \\
r\text{RMSD: 0.108} \\
r\text{MSD: 0.002}

-\text{-ad} \, 250 \, -\text{lw} \, 1.6e-4 \, -\text{lr} \, -14 \\
\text{repeated 32 times} \quad \text{samp/sec: 123.3} \\
r\text{RMSD: 0.153} \\
r\text{MSD: 0.004}
Same Effect: Increases noise, decreases time
Reduce -lr: little effect on time without large bias

- **ad 4000 -lw 1e-5 -lr -10**
  - repeated 32 times
  - samp/sec: 8.4
  - rRMSD: 0.035
  - rMSD: -0.003

- **ad 4000 -lw 1e-5 -lr -6**
  - repeated 32 times
  - samp/sec: 8.1
  - rRMSD: 0.036
  - rMSD: -0.037

- **ad 4000 -lw 1e-5 -lr -2**
  - repeated 32 times
  - samp/sec: 21.3
  - rRMSD: 0.054
  - rMSD: -0.307

- **ad 1000 -lw 4e-5 -lr -14**
  - repeated 32 times
  - samp/sec: 32.7
  - rRMSD: 0.072

- **ad 500 -lw 8e-5 -lr -14**
  - repeated 32 times
  - samp/sec: 66.1
  - rRMSD: 0.108
  - rMSD: 0.002

- **ad 250 -lw 1.6e-4 -lr -14**
  - repeated 32 times
  - samp/sec: 123.3
  - rRMSD: 0.153
  - rMSD: 0.004

- **ad 1000 -lw 4e-5 -lr -10**
  - repeated 32 times
  - samp/sec: 32.7
  - rRMSD: 0.072

- **ad 250 -lw 1.6e-4 -lr -14**
  - repeated 32 times
  - samp/sec: 123.3
  - rRMSD: 0.153
  - rMSD: 0.004
Determining Settings: Illuminance Based

benchmark: -ad 4000 -lw 1e-5 -lr -14
repeated 8 x 32 times samp/sec: 0.3
rRMSD: 0.007  rMSD: 0.000
Reduce -ad (proportionally adjust -lw)
initial weight of an illuminance ray is \( \pi \) so initial divisions are higher

- ad 1000 -lw 4e-5 -lr -14
  repeated 32 times  samp/sec: 4.8
tRMSD: 0.049  rMSD: -0.011
luminance:
  repeated 32 times  samp/sec: 32.7
  rRMSD: 0.072  rMSD: 0.000

- ad 500 -lw 8e-5 -lr -14
  repeated 32 times  samp/sec: 11.4
tRMSD: 0.066  rMSD: -0.014
luminance:
  repeated 32 times  samp/sec: 66.1
  rRMSD: 0.108  rMSD: 0.002

- ad 250 -lw 1.6e-4 -lr -14
  repeated 32 times  samp/sec: 14.9
tRMSD: 0.113  rMSD: -0.019
luminance:
  repeated 32 times  samp/sec: 123.3
  rRMSD: 0.153  rMSD: 0.004
Reduce -lr

illuminance consumes one bounce

- ad 4000 -lw 1e-5 -lr -10
repeated 32 times
samp/sec: 1.8
rRMSD: 0.021
rMSD: 0.002

- ad 4000 -lw 1e-5 -lr -6
repeated 32 times
samp/sec: 1.8
rRMSD: 0.025
rMSD: -0.026

- ad 4000 -lw 1e-5 -lr -2
repeated 32 times
samp/sec: 4.9
rRMSD: 0.032
rMSD: -0.273

luminance:
repeated 32 times
samp/sec: 8.4
rRMSD: 0.035
rMSD: -0.003

luminance:
repeated 32 times
samp/sec: 8.1
rRMSD: 0.036
rMSD: -0.037

luminance:
repeated 32 times
samp/sec: 21.3
rRMSD: 0.054
rMSD: -0.307
Determining Settings: rcontrib (sky receiver)
sky contribution only (w/o sun)

MF:1 -ad 4000 -lw 1e-5 -lr -14
repeated 32 times
samp/sec: 6.3
rRMSD: 0.033
rMSD: -0.026

MF:2 -ad 4000 -lw 1e-5 -lr -14
repeated 32 times
samp/sec: 6.1
rRMSD: 0.033
rMSD: -0.028

MF:4 -ad 4000 -lw 1e-5 -lr -14
repeated 32 times
samp/sec: 6.2
rRMSD: 0.033
rMSD: -0.025
solar energy in sky patch (w/ sun)

MF:1 -ad 4000 -lw 1e-5 -lr -14
repeated 32 times
samp/sec: 9.0
rRMSD: 0.128
rMSD: 0.065

MF:2 -ad 4000 -lw 1e-5 -lr -14
repeated 32 times
samp/sec: 8.4
rRMSD: 0.225
rMSD: 0.039

MF:4 -ad 4000 -lw 1e-5 -lr -14
repeated 32 times
samp/sec: 6.4
rRMSD: 0.390
rMSD: 0.001
solar energy in sky patch

MF:1 -ad 4000 -lw 1e-5 -lr -14
repeated 8 x 32 times
samp/sec: 0.9
rRMSD: 0.045
rMSD: 0.060

MF:2 -ad 4000 -lw 1e-5 -lr -14
repeated 8 x 32 times
samp/sec: 0.9
rRMSD: 0.083
rMSD: 0.036

MF:4 -ad 4000 -lw 1e-5 -lr -14
repeated 8 x 32 times
samp/sec: 0.9
rRMSD: 0.164
rMSD: -0.007
Determining Settings: rcontrib (window receiver)
integrated (trans/sky) vs. specular

- ALL -ad 4000 -lw 1e-5 -lr -14
  repeated 32 times
  samp/sec: 11.5
  rRMSD: 0.020
  rMSD: 0.000

- PATCH_001
  repeated 32 times
  samp/sec: 11.5
  rRMSD: 0.459
  rMSD: 0.010

- PATCH_076
  repeated 32 times
  samp/sec: 11.5
  rRMSD: 0.446
  rMSD: -0.007
integrated (trans/sky) vs. specular

ALL -ad 16000 -lw 1e-8 -lr -14
repeated 32 times
samp/sec: 0.7
rRMSD: 0.009

PATCH_001
repeated 32 times
samp/sec: 0.7
rRMSD: 0.213

PATCH_076
repeated 32 times
samp/sec: 0.7
rRMSD: 0.253
sampling a point
Existing Options For Sampling a Point

<table>
<thead>
<tr>
<th>Samples</th>
<th>$10^6$ samples</th>
<th>$10^3$ samples</th>
<th>1 sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Information</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
</tbody>
</table>

$$DGP = 5.87 \cdot 10^{-5} E_v + 9.18 \cdot 10^{-2} \log_{10} \left( \frac{1}{n} \sum_{i=1}^{L} L^2_s \omega_{s,i} E_{1.87} v P^2_i \right) + 0.16$$

$$DGP = 6.22 \cdot 10^{-5} E_v + 0.184$$

$$A \cdot E_v + B \cdot \log_{10} \left( \frac{1}{n} \sum_{i=1}^{L} L^2_s \omega_{s,i} E_{1.87} v P^2_i \right) + C$$

$$A = \begin{pmatrix} a_1^1 & a_2^1 & \ldots & a_t^1 \\ a_1^v & a_2^v & \ldots & a_t^v \end{pmatrix}$$

$$B = \begin{pmatrix} b_1^1 & b_2^1 & \ldots & b_t^1 \\ b_1^v & b_2^v & \ldots & b_t^v \end{pmatrix}$$
### Existing Options For Sampling a Point

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<td>Low</td>
</tr>
</tbody>
</table>

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-2} \log_{10} \left( 1 + \sum_{i=1}^{n} L_{s,i} \omega_{s,i} E^{1.87} v P_{2i} \right) + 0.16$$

$$DGPs = 6.22 \times 10^{-5} E_v + 0... = A \cdot E_v + B \cdot \log_{10} \left( 1 + \sum_{i=1}^{n} L_{s,i} \omega_{s,i} E^{1.87} v P_{2i} \right) + C$$

$$A = \begin{bmatrix} a_1 \ 1 \ a_2 \ 1 \ \vdots \ \vdots \ \vdots \ \vdots \ a_1 \ t \ a_v \ t \end{bmatrix}$$

$$B = \begin{bmatrix} b_1 \ 1 \ b_2 \ 1 \ \vdots \ \vdots \ \vdots \ \vdots \ b_1 \ t \ b_v \ t \end{bmatrix}$$
### The Potential in Sampling

<table>
<thead>
<tr>
<th>Samples</th>
<th>10⁶ samples</th>
<th>7 Samples</th>
<th>1 sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
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</table>

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-2} \log_{10} \left( 1 + \sum_{i=1}^{n} L_{s,i} \omega_{s,i} E_{1.87} V P_{2}^{i} \right) + 0.16$$

$$\text{DGPs} = 6.22 \times 10^{-5} E_v + 0.164$$
The Potential in Sampling

<table>
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<tr>
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</thead>
<tbody>
<tr>
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<td>High</td>
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<td>Medium</td>
</tr>
<tr>
<td>Information</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

\[
DGP = 5.87 \cdot 10^{-5} E_v + 9.18 \cdot 10^{-2} \log_{10} \left( 1 + \sum_{i=1}^{n} L_{2s,i} \omega_{s,i} E_{1.87} v_{P_i}^2 \right) + 0.16
\]

\[
DGP = 6.22 \cdot 10^{-5} E_v + \ldots = \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1t} \\ a_{21} & a_{22} & \ldots & a_{2t} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \ldots & a_{nt} \end{bmatrix}
\]

\[
B = \begin{bmatrix} b_{11} & b_{12} & \ldots & b_{1t} \\ b_{21} & b_{22} & \ldots & b_{2t} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \ldots & b_{nt} \end{bmatrix}
\]
Wavelet Decomposition
Wavelet Decomposition
Original

Wavelet Decomposition

> 0.1 cd/m² = 35%
> 1 cd/m² = 12%
> 10 cd/m² = 4%
> 100 cd/m² = 0.7%
Wavelet Compression
Reconstruction Through Sampling
Component Sampling

Sky Contribution Coefficients

Sun Contribution Coefficients

sky[sun index]

Sky Vector

Solar Radiance

100,000
39,810
15,850
6,310
2,510
1,000
400
160
60
25
Clear glazing w/ view to direct sun and semi-specular reflection

Results

Raytraverse

Reference / High Resolution

Uniform / Equal Sampling

+4.9%  
+1.3%  
relative deviation

Ev = 28,140 lux
UGR = 65.9

+7.2%  
-11.2%  
relative deviation
Results

Fabric shade w/ view to direct sun

Raytraverse

Reference / High Resolution

Uniform / Equal Sampling

-0.8%  Ev = 1,800 lux  -0.7%

-19.3%

+1.4%  UGR = 46.3  -19.3%

cd/m²
Venetian blinds w/ partial view to direct sun

Results

Raytraverse

Reference / High Resolution

Uniform / Equal Sampling

<table>
<thead>
<tr>
<th>Relative Deviation</th>
<th>Reference / High Resolution</th>
<th>Uniform / Equal Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5.6%</td>
<td>-83.1%</td>
<td>-51.8%</td>
</tr>
<tr>
<td>+4.0%</td>
<td>Ev = 14,330 lux</td>
<td>UGR = 63.4</td>
</tr>
</tbody>
</table>

Ev = 14,330 lux
UGR = 63.4
Venetian blinds w/ semi-specular reflection

Results

Raytraverse

Reference / High Resolution

Uniform / Equal Sampling

+3.2%
+5.2%

relative deviation

Ev = 1,400 lux

UGR = 27.5

-15.1%
+3.0%
Clear glazing w/ exterior specular reflection

Raytraverse

Reference / High Resolution

Uniform / Equal Sampling

Results

<table>
<thead>
<tr>
<th>Method</th>
<th>Relative Deviation</th>
<th>lux</th>
<th>UGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raytraverse</td>
<td>-5.1%</td>
<td>Ev=6,820</td>
<td>UGR=47.1</td>
</tr>
<tr>
<td>Reference / High Resolution</td>
<td>+5.2%</td>
<td>-23.7%</td>
<td></td>
</tr>
<tr>
<td>Uniform / Equal Sampling</td>
<td></td>
<td>-40.2%</td>
<td></td>
</tr>
</tbody>
</table>
Dot frit with partial view to direct sun

**Results**

<table>
<thead>
<tr>
<th>Method</th>
<th>Relative Deviation</th>
<th>Reference</th>
<th>High Resolution</th>
<th>Uniform</th>
<th>Equal Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raytraverse</td>
<td>-3.0%</td>
<td>100,000</td>
<td>39,810</td>
<td>15,850</td>
<td>6,310</td>
</tr>
<tr>
<td></td>
<td>-0.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>-17.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Resolution</td>
<td>+1.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uniform</td>
<td>-3.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal Sampling</td>
<td>-0.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ev = 27,430 lux  
UGR = 59.4
sampling the sky
Annual Sky Conditions

Perez sky model + discretized sky-patches

Solar Position
each sample is complete description of a point
several metrics may be needed: contrast
and brightness
Sampling Weights

Level 0

Level 1

Level 2

Level 0-3
Component Sampling

<table>
<thead>
<tr>
<th></th>
<th>Direct</th>
<th>Indirect</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sky</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Use Sky for Sun

Direct + Indirect = Total

Sky Patch + Sun = Total
Results

Reference (rpict)
-x 2700 -aa 0 -ad 250 -lr -14 -lw 1.58e-4 -ps 3 -pt .04 | pfilt -x /3 -y /3
simulation times (per view and sky, assumes 4,294 timesteps, single thread)
2:20:08

2-phase
-sun direct / skypatch indirect
-x 900 -ad 8000 -lw 5.5e-5 -lr -14
2-phase
0:00:37

raytraverse
-sun full depth
-sky: -ad 16250 -lw 2.46e-5 -lr -14
sun: -ad 1000 -lw 4e-5 -as 0 -lr -14
2^6 initial sampling resolution
0:00:15

raytraverse-d
-sun direct / skypatch indirect
-sky: -c 4 -ad 16250 -lw 2.46e-5 -lr -14
2^6 initial sampling resolution
0:00:02
Illuminance

2-phase

Raytraverse

Raytraverse-d

Reference
DGP

2-phase

Raytraverse

Raytraverse-d

Reference

Reference

Reference
Illuminance

Relative Illuminance Mean Absolute Deviation

Raytraverse

MAE MSD

2-phase

Raytraverse-d

Series 00 01 02 03 04 05

View 100 101 102 103 104
Efficiency

computation time

storage

<table>
<thead>
<tr>
<th>method</th>
<th>processor hours/point</th>
<th>gigabytes/point</th>
</tr>
</thead>
<tbody>
<tr>
<td>reference</td>
<td>20,000</td>
<td>23.66</td>
</tr>
<tr>
<td>2-phase</td>
<td>88</td>
<td>1.71</td>
</tr>
<tr>
<td>raytraverse</td>
<td>36</td>
<td>0.47</td>
</tr>
<tr>
<td>raytraverse-d</td>
<td>36</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Fixed

per timestep (suns + evaluation)

total

4.16
Modeling Interlude

what does it all mean?
Throughout the rendering and evaluation process, the models we use are a combination of:

- physical/process models (solar position, light-transport, material interaction).
- statistical models (TMY)
- correlated measurement models (perez)
- interpolated measurement models (BSDF)
- and mixed models combining some of the above (DGP, DA)
Perez, TMY, and Hourly Sun Positions

Los Angeles Intl. Airport

TMY-X
climate.onebuilding.org
TMY/ISO 15927-4:2005

TMY-3
www.energyplus.net
sandia method + direct radiation
Perez, TMY, and Hourly Sun Positions

Hours with direct sun
HH:00 ..... 408
HH:10 ..... 447
HH:20 ..... 438
HH:30 ..... 453
HH:40 ..... 453
HH:50 ..... 429
rel. dev. ..... 7%
(a larger error than any of the simulations)
Perez, TMY, and Hourly Sun Positions

The annual sky matrix is a sampling of sun positions (which may or may not be representative) within a sample of sky conditions (which may or may not be representative and are integrated hourly measurements used as point samples) modeled with an experimentally derived least square fit of measured data.
CBDM for predictive modelling

It is not possible, using either TMY or site-measured weather data to predict future conditions at a particular time. Instead, the best outcome is a representative distribution of likely conditions with a plausible temporal sequence driven by solar position.
CBDM for predictive modelling

when comparing two simulation methods, some level of variance, and even extreme outliers, may not be significant if both represent the same true underlying distribution.
CBDM for predictive modelling

when comparing two simulation methods, some level of variance, and even extreme outliers, may not be significant if both represent the same true underlying distribution.
CBDM for predictive modelling

Should we aim for one to one matching with hourly reference data? Or should we aim for representing a continuous distribution?

frequency of solar positions with direct normal > 50 w/m² (LAX)
Distribution of Solar Samples

N=457

N=413
sampling an area
review of sampling rays from a point

---

**Initialize**

- **Weights**
- **Vectors**

**Draw**

- 5.625° to 0.176°
- Loop Through Frequencies of DWT
- **Weights**
- **Vectors**
- **Results**

**Sample**

- **Weights**
- **Vectors**
- **store**

**Draw**

- **Weights**
- **Vectors**
- **Results**

---

D =

N = sum(D > t)

choose N samples according to D

---

upsample
convolve
abs

---

abs

N = sum(D > t)

choose N samples according to D

---

**Weights**

- 

**Vectors**

- 

---

```
[ -0.5 1.0 -0.5 ]
[ 1.0 ]
[ -0.5 ]
[ 0 1.0 0 ]
[ 0 0 -0.5 ]
```

---

**Draw**

- **Weights**
- **Vectors**

---

```
+ + +
```

---

```
D =

N = sum(D > t)

choose N samples according to D

```
Sampling points on an area

Initialize

Weights

Vectors

Draw

Loop

Through Frequencies of DWT

N = sum(D > t)

choose N samples according to D

Result

Sample

2m to 0.25m

Weights

Vectors

store

Draw

Weights

Estimate @ next level

convolve abs max mask

N = \sum(D > t)

choose N samples according to D

Vectors

Avg. Lum

Contrast

Peak X

Peak Y

Suns Sampler

Values:

Weights = [average luminance, log(GCR)]

Vector = a solar position (sx, sy, sz)

Result = a LightField (the result of an Area Sampler)

Sample Function:

An Area Sampler - calculate the light incident on a plane for all points and directions.

Area Sampler

Values:

Weight = [average luminance, log(GCR)]

Vector = a view point (dx, dy, dz)

Result = a LightPoint (the result of a Point Sampler)

Sample Function:

A Point Sampler - calculate the light incident on a point from all directions.

Point Sampler

Values:

Weight = max(Luminance or Coefficient of all sources)

Vector = view ray at a point (x, y, z, dx, dy, dz)

Result = Luminance or Coefficient for all sources

Sample Function:

A renderer - calculates light incident on a point from a view direction

Loop Through Frequencies of DWT

Sampling points on an area
Area Sampling Loop - Level 1

Vectors

Weights

Detail
Area Sampling Loop - Level 2

Vectors

Weights

Detail
Area Sampling Loop - Level 3

Vectors
sampling sun positions on an area

For each sun position, area sampler provides final weights across area

Convolve over (Usky, Vsky) to find detail between sun positions.

Produce sun position vectors at every region that has a position above threshold

Mask area sampler to exclude low detail regions for each source
Important Links

Documentation
• Installation Instructions
• Getting Started
• Tutorials
• complete command line reference
• API documentation
• Project Links and Citations

Github
https://github.com/stephanwaz/raytraverse

PyPI
https://pypi.org/project/raytraverse/
Installation

Raytraverse runs on Mac or Linux and Requires Python >=3.6

I recommend installing any python package in a virtual environment:

```bash
python3 -m venv <myenv>
source <myenv>/bin/activate
```

(you can put the activate line in your .bash_profile if you are forgetful and lazy like me. Terminal will look like this:

```
(<myenv>) my-computer:~me$
```

The easiest way to install raytraverse is with pip:

```
pip install --upgrade pip setuptools wheel
pip install raytraverse
```

or if you have cloned this repository:

```
cd path/to/this/file
pip install .
```

I am working on putting together a pyinstaller for those who do not want to manage their own python environment, but this will likely be a Mac only option. check the raytraverse.readthedocs.io for updates
Installation

At present, installing raytraverse will also install the following radiance binaries (another good reason to use a virtualenv):

- rtrace
- rcontrib
- total
- cnt
- rcalc
- getinfo
- vwrays
- pvalue
- pcompos
- pcomb
- pfilt
- oconv
- gendaylit
- xform

raytraverse doesn’t actually depend on most of these (other than oconv, but they are necessary for testing)
Wait, How does Raytraverse not depend on rtrace?

Rtrace

class raytraverse.renderer.Rtrace(rayargs=None, scene=None, nproc=None, default_args=True, direct=False)  
Bases: raytraverse.renderer.radiancerenderer.RadianceRenderer
	singleton wrapper for c++ raytraverse.crenderer.cRtrace class

this class sets default arguments, helps with initialization and setting cpu limits of the cRtrace instance. see raytraverse.crenderer.cRtrace for more details.

Parameters:
- rayargs (str, optional) – argument string (options and flags only) raises ValueError if arguments are not recognized by cRtrace.
- scene (str, optional) – path to octree
- nproc (int, optional) – if None, sets nproc to cpu count, or the RAYTRAVERSE_PROC_CAP environment variable
- default_args (bool, optional) – if True, prepend default args to rayargs parameter
- direct (bool, optional) – if True use Rtrace.directargs in place of default (also if True, sets default_args to True).

Examples

Basic Initialization and call:

```python
r = renderer.Rtrace(args, scene)  
an = rvecs)  
# ans.shape -> (vecs.shape[0], 1)
```

If rayargs include cache files (ambient cache or photon map) be careful with updating sources. If you are going to swap sources, update the arguments as well with the new paths:

```python
r = renderer.Rtrace(args, scene)  
r.set_args(args.replace("temp.amb", "temp2.amb"))  
r.load_source(srcdef)
```

Note that if you are using ambient caching, you must give an ambient file, because without a file ambient values are not shared across processes or successive calls to the instance.

Rcontrib

class raytraverse.renderer.Rcontrib(rayargs=None, scene=None, nproc=None, skyres=10.0, modname=None, ground=True, default_args=True)  
Bases: raytraverse.renderer.radiancerenderer.RadianceRenderer
	singleton wrapper for c++ raytraverse.crenderer.cRcontrib class

this class sets default arguments, helps with initialization and setting cpu limits of the cRcontrib instance. see raytraverse.crenderer.cRcontrib for more details.

Parameters:
- rayargs (str, optional) – argument string (options and flags only) raises ValueError if arguments are not recognized by cRcontrib.
- scene (str, optional) – path to octree
- nproc (int, optional) – if None, sets nproc to cpu count, or the RAYTRAVERSE_PROC_CAP environment variable
- skyres (float, optional) – approximate resolution for skypatch subdivision (in degrees). Patches will have (rounded) size skyres x skyres. So if skyres=10, each patch will be 100 sq. degrees (0.03046174197 steradians) and there will be 18 * 18 = 324 sky patches.
- modname (str, optional) – passed the -m option of cRcontrib initialization
- ground (bool, optional) – if True include a ground source (included as a final bin)
- default_args (bool, optional) – if True, preprend default args to rayargs parameter

Examples

Basic Initialization and call:

```python
r = renderer.Rcontrib(args, scene)  
an = rvecs)  
# ans.shape -> (vecs.shape[0], 325)
```
The Command Line Interface

$ raytraverse --help

Usage: raytraverse [OPTIONS] COMMAND1 [ARGS]... [COMMAND2 [ARGS]...]...

Commands:
- area: define sampling area
- evaluate: evaluate metrics
- examplescript: print an example workflow for script based/api level access to raytraverse
- images: render images
- imgmetric: calculate metrics for hdr images, similar to evalglare but without glare source grouping, equivalent to -r 0 in evalglare.
- pull: flatten/unroll results into 2d tsv data
- scene: define scene files for renderer and output directory
- skydata: define sky conditions for evaluation
- skyengine: initialize engine for skyrun
- skyrun: run scene under sky for a set of points (defined by area)
- sunengine: initialize engine for sunrun
- sunrun: run scene for a set of suns (defined by suns) for a set of points (defined by area)
- suns: define solar sampling space
The Command Line Interface

$ raytraverse --template > settings.cfg

Set up scene and output directory

[raytraverse_scene]
log = True
out = None
overwrite = False
reload = True
scene = None

Set up sampling area

[raytraverse_area]
name = plan
ptres = 1.0
rotation = 0.0
static_points = None
zheight = None
zone = None

Set up sun sampling (candidates or transit)

[raytraverse_suns]
epwloc = False
loc = None
name = suns
printdata = False
printlevel = None
skyro = 0.0
sunres = 30.0
The Command Line Interface

$ raytraverse --template > settings.cfg

Sky matrix data

```
[raytraverse_skydata]
ground_fac = 0.15
loc = None
minalt = 2.0
mindiff = 5.0
name = skydata
reload = True
skyres = 10.0
skyro = 0.0
wea = None
```

Point sampler for sky coefficients

```
[raytraverse_skyengine]
accuracy = 1.0
dcompargs = -ab 1
default_args = True
fdres = 9
idres = 5
rayargs = None
skyres = 10.0
```

Point sampler for sun coefficients

```
[raytraverse_sunengine]
accuracy = 1.0
dcompargs = -ab 0
default_args = True
fdres = 10
idres = 5
maxspec = 0.2
rayargs = None
slimit = 0.01
speclevel = 9
```
### The Command Line Interface

```bash
$ raytraverse --template > settings.cfg

#### Sky area sampler (main command)

```bash
[raytraverse_skyrun]
accuracy = 1.0
dcomp = True
jitter = True
nlev = 3
overwrite = False
plotp = False
```

#### Sun area sampler (main command)

```bash
[raytraverse_sunrun]
accuracy = 1.0
guided = True
jitter = True
nlev = 3
overwrite = False
plotp = False
recover = True
srcaccuracy = 1.0
srcjitter = True
srcnlev = 3
```

#### Output image generations

```bash
[raytraverse_images]
basename = results
dcomp = True
interpolate = False
namebyindex = False
res = 800
sdirs = None
sensors = None
skymask = None
sunonly = False
viewangle = 180.0
```

```bash
$ raytraverse -c settings.cfg skyrun sunrun
```
The Command Line Interface

$ raytraverse --template > settings.cfg

```
metric calculation
[raytraverse_evaluate]
basename = results
dcomp = True
metrics = illum dgp ugp
npz = True
sdirs = None
sensors = None
skymask = None
sunonly = False
viewangle = 180.0

utility: calculate metrics on hdr images (like evalglare)
[raytraverse_imgmetric]
basename = img_metrics
imgs = None
metrics = illum dgp ugp
npz = True
parallel = True
peaka = 6.7967e-05
peakn = True
peakr = 4.0
peakt = 100000.0
scale = 179.0
threshold = 2000.0

Output metric result tables
[raytraverse_pull]
col = metric
header = True
imgfilter = None
lr = None
metricfilter = None
order = point view sky
ptfilter = None
rrowlabel = True
skyfilter = None
viewfilter = None
```

$ raytraverse -c settings.cfg evaluate pull
Thank You

Stephen Wasilewski

HOCHSCHULE EASE
LUZERN Lars Grobe PhD Roland Schregle PhD

EPFL LIPID Jan Wienold PhD Marilyne Andersen PhD

This research is funded by the Swiss National Science Foundation SNSF under grant #179067 as part of the project Light fields in climate-based daylight modeling for spatio-temporal glare assessment http://p3.snf.ch/project-179067
Appendix: Error by Metric
Illuminance - Error by Illuminance

The diagram illustrates the error in illuminance across different illuminance levels. The x-axis represents the illuminance values, while the y-axis shows the relative error. The graph compares three methods: 2-phase, raytraverse, and raytraverse-d. The error distribution is shown through box plots, indicating the spread and central tendency of the errors for each method. The error percentage at 97.5%, 2.5%, 25%, 50%, and 75% is also indicated on the right side of the graph.
UGP - Error by View

The graph shows the distribution of error values for different views and conditions. The x-axis represents the view, and the y-axis represents the error values. There are separate distributions for 2-phase raytraverse, raytraverse, and raytraverse-d, each indicated by different colors.

Key observations:
- The error values range from approximately -0.1 to 0.1.
- The majority of error values are close to zero, indicating good accuracy.
- There are outliers in certain views and conditions, suggesting variability.

Legend:
- Purple: 2-phase raytraverse
- Red: raytraverse
- Yellow: raytraverse-d

Percentile values are also indicated on the right side of the graph.