High-Tune: RenDeRer

Najda Villefranque[1]
najda.villefranque@lmd.ipsl.fr

Vincent Eymet[2]
vincent.eymet@meso-star.com

Vincent Forest[2]
vincent.forest@meso-star.com

[1]CNRS/LMD, [2]|Méso|Star>

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Overview

Monte Carlo rendering engine of scenes with inhomogeneous media

- Backward path-tracing algorithm [Villefranque et al., 2019]

Pure CPU solver

- C ANSI [Kernighan, 1988]
- GNU/Linux 64-bits
- Mixed parallelisation (OpenMP/OpenMPI)

Command line interface

UNIX philosophy in mind

Write programs that do one thing and do it well

- Write readable, simple, small, transparent and robust programs

Write programs that work together

- Use composition

Write programs that handle text streams...

- *... because that is a universal interface*

"When in doubt, use brute force" *(K. Thompson)*

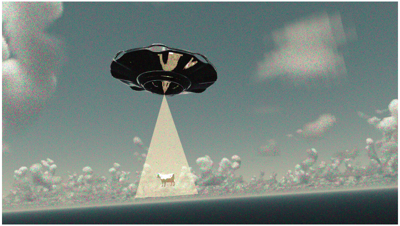
- Monte Carlo!

Libre Software [GPL, 2007]

Hacked by its community

- Study, modify and extend both data and code

(a) Spectral reflectivity support

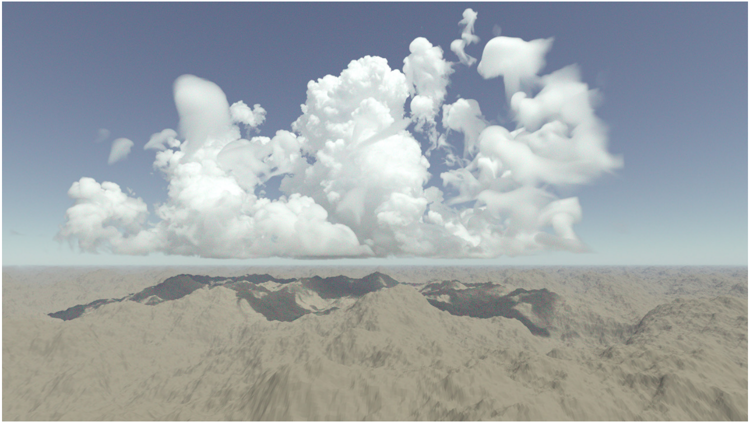


(b) Handling laser sheet [Sans et al., 2021]

History

2018, 2019[1]

- Rendering of cloudy atmospheres [Villefranque et al., 2019]
- Arbitrary ground geometries

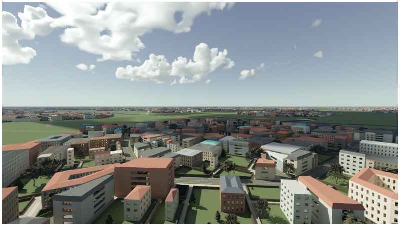


[1]High-Tune ANR-16-CE01-0010 - CNRS/CNRM, CNRS/LMD, LAPLACE

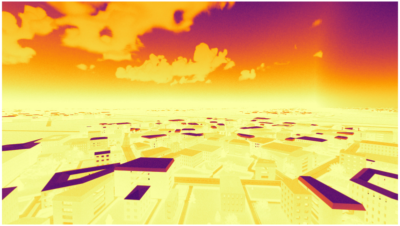
History

2020[2]

- Infrared rendering of cloudy atmospheres
- Solve upward and downward atmospheric fluxes (visible & infrared)
- Ground geometry with spectral reflectivity [Kotthaus et al., 2013]



(a) CIE XYZ rendering



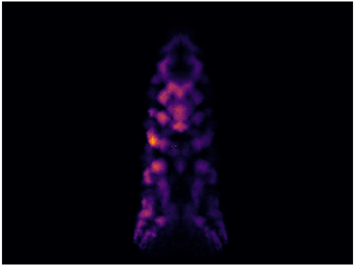
(b) Infrared rendering in 9 μm and 10 μm

[2] ModRadUrb Ademe MODEVAL-URBA-2019 - CNRS/CNRM, |Méso|Star>

To come up

2020, 2021[3]

- Radiative transfer in soot aggregates illuminated by a laser [Sans et al., 2021]



Monochromatic shortwave rendering at 532 nm

2021[4], ...

- Line sampling: a whole new class of radiative transfer algorithms

[3] Astoria ANR-18-CE05-0015 - ONERA, CNRS/RAPSODEE, CORIA

[4] MCG-Rad ANR-18-CE46-0012 - IRIT, CNRS/LMD, LAPLACE

Data

Input data

- 1D atmospheric profile
- 3D cloud field
- Water droplets properties
- Ground geometry and materials

Output data

- Image of per pixel Monte Carlo estimations

Input data - 1D atmospheric profile

RRTM-G optical properties computed from an 1D profile of T, P, q

- Handle horizontal variation of q by pre-processing N water vapor concentrations
- Absorption coefficient (visible & infrared)
- Scattering coefficient (visible)

k-distributions

- Computed with `ecRad` [Hogan and Bozzo, 2016]
- Tabulated per x_{H_2O} to handle local variations
- Interpolated at runtime according to x_{H_2O}

Input data - 3D cloud field

Computed from Large Eddy Simulations
[Lafore et al., 1997, Lac et al., 2018]

Per cell data

- Water vapor mixing ratio in kg of water per m^3 of dry air
- Liquid water in suspension mixing ratio in kg of water per m^3 of dry air
- Pressure in Pascal
- Temperature in Kelvin

Input data - Water droplets properties

Computed from a Mie code [Mishchenko et al., 2002]

- Discretised over the visible & infrared spectral ranges
- Integrated onto one water droplet distribution
  - In `htspk`: lognormal distribution with an effective radius of 10 μm and a standard deviation of 0.1 μm

Per wavelength data

- Massic absorption cross-sections
- Massic scattering cross-sections
- Asymmetric parameters of the equivalent Henyey-Greenstein phase function

Input data - Ground surface

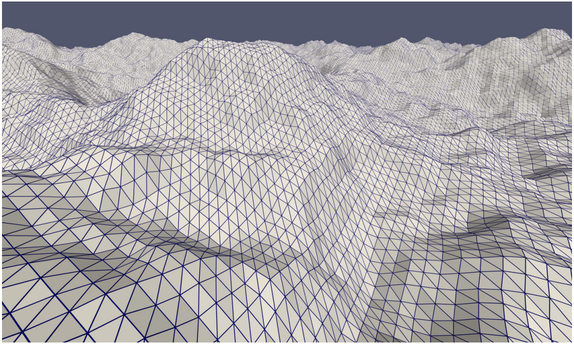
Arbitrary geometry stored in an `obj`-like format

Spectrally varying reflectivity (visible & infrared)

- 2 types of BRDF: lambertian and specular

```
# List of vertices
v 0 0 367.196
v 19.5312 0 353.952
v 39.0625 0 347.371
v 58.5938 0 345.122
v 78.125 0 340.736
...
v 9980.47 10000 390.285
v 10000 10000 367.196

# List of triangles
usemtl air:rock
f 1 514 2
f 2 514 515
f 2 515 3
f 3 515 516
...
f 262655 263168 262656
f 262656 263168 263169
```



Output data - Rendered image

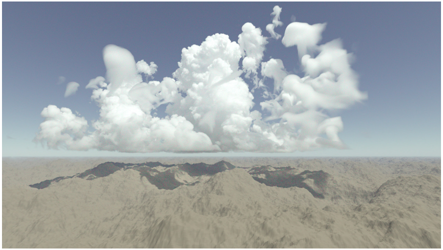
Array of per pixel Monte Carlo estimations

Camera image

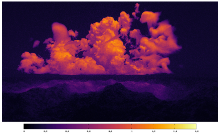
- CIE XYZ [CIE, 1931]
- Shortwave
- Longwave

Flux map

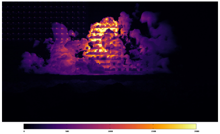
- Shortwave
- Longwave



(a) XYZ radiance



(b) X standard error



(c) Time per realisation

Beyond the renderer

Web site

- `www.meso-star.com/projects/high-tune/high-tune.html`

Reference documentation

- `man` pages

High-Tune: Starter Pack (`htspk`)

- Set of "ready for use" input data
- `www.meso-star.com/projects/high-tune/starter-pack.html`

High-Tune: Post Process (`htpp`)

- Post treatment of the generated images

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Kotthaus, S., Smith, T., Wooster, M., and Grimmond, S. (2013).
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The Meso-NH Atmospheric Simulation System. Part I: adiabatic formulation and control simulations.
Annales Geophysicae, 16(1):90–109.

Mishchenko, M. I., Travis, L. D., and Lacis, A. A. (2002).
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Sans, M., Eymet, V., Villefranque, N., El Hafi, M., Fourner, R., and Forest, V. (2021).
Null-collision meshless Monte-Carlo - A new backward integral formulation designed for laser-source emission in absorbing/emitting inhomogeneous media.
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Villefranque, N., Fournier, R., Couvreux, F., Blanco, S., Cornet, C., Eymet, V., Forest, V., and Tregan, J.-M. (2019).
A path-tracing monte carlo library for 3-d radiative transfer in highly resolved cloudy atmospheres.
Journal of Advances in Modeling Earth Systems, 11(8):2449–2473.

Converting a intensity spectral signal to a color

Rendering in the XYZ colorimetry space [CIE, 1931]

$$X = \int_0^{+\infty} \bar{x}(\lambda) L_\lambda(\vec{x}, -\vec{u}) d\lambda \qquad (1)$$

$$Y = \int_0^{+\infty} \bar{y}(\lambda) L_\lambda(\vec{x}, -\vec{u}) d\lambda \qquad (2)$$

$$Z = \int_0^{+\infty} \bar{z}(\lambda) L_\lambda(\vec{x}, -\vec{u}) d\lambda \qquad (3)$$

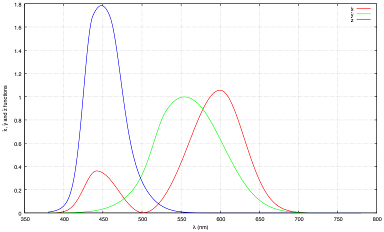


Figure: Functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ et $\bar{z}(\lambda)$

XYZ → sRGB conversion : "High-Tune: Post-Process"

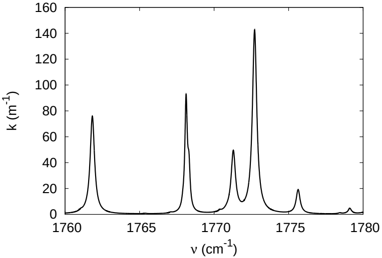
- https://gitlab.com/meso-star/htpp.git
- Tone mapping [Hable, 2010]
- XYZ → sRGB conversion : $C_{sRGB} = [M].C_{XYZ}$
- gamma correction

The k-distribution spectral model (1/4)

The spectral integration needs to be performed over the $[\nu_{min}, \nu_{max}]$ interval :

$$\frac{1}{\nu_{max} - \nu_{min}} \int_{\nu_{min}}^{\nu_{max}} A(\nu) d\nu \tag{4}$$

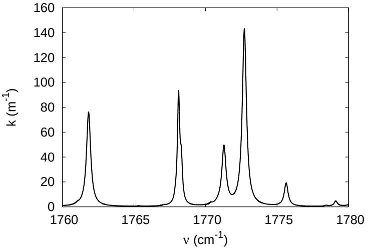
With A the monochromatic radiative quantity.

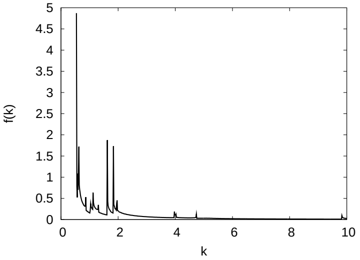


The k-distribution spectral model (2/4)

$$\frac{1}{\nu_{max} - \nu_{min}} \int_{\nu_{min}}^{\nu_{max}} A(\nu) d\nu = \int_0^{+\infty} A(k) f(k) dk \qquad (5)$$

$f(k)$: distribution function for $k(\nu)$
$f(k)dk$: fraction of ν_{max}-ν_{min} where $k \in [k; k + dk]$

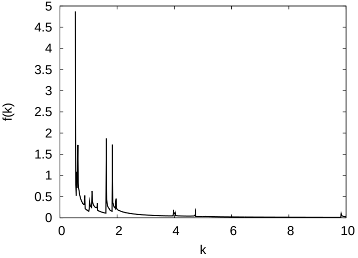


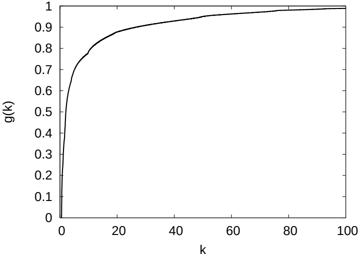


The k-distribution spectral model (3/4)

$$\frac{1}{\nu_{max} - \nu_{min}} \int_{\nu_{min}}^{\nu_{max}} A(\nu) d\nu = \int_0^{+\infty} A(k) f(k) dk = \int_0^1 A(k(g)) dg \quad (6)$$

with $g(k) = \int_0^k f(k')dk'$ the cumulative of $f(k)$





The k-distribution spectral model (4/4)

$$\frac{1}{\nu_{max} - \nu_{min}} \int_{\nu_{min}}^{\nu_{max}} A(\nu) d\nu = \int_0^1 A(k(g)) dg \approx \sum_{i=1}^{N} A(k(g_i)) \omega_i \quad (7)$$

g_i : quadrature abscissae
ω_i : quadrature weight
$k(g_i) \equiv k_i$: values of k

Advantage

Instead of performing thousands of monochromatic radiative transfer computations, only $N \approx 10$ independant computations are required for a spectral interval a few tenths of cm^{-1} wide.

Disadvantage

For a heterogeneous medium, a small error (≈ 5 %) is introduced: when T or P change, the $k(\nu)$ spectrum is modified and a given value of g_i/k_i no longer corresponds to the same pool of frequencies. The $k(\nu)$ spectrum is therefore supposed to be homothetic when thermodynamic conditions are modified, in order to assume a radiative transfer computation for a given k_i is equivalent to a series of monochromatic radiative transfer computations ("correlated-k" hypothesis, more or less relevant).

Using High-Tune: RenDeRer

Install

Prerequisites

- git and git-lfs
- GNU Compuler Collection (version $\geq$ 4.8)
- CMake (version $\geq$ 3)
- NetCDF library and headers (version $\geq$ 4)
- OpenMPI library and headers
- AsciiDoc to generate the man pages (optional)

Install htrdr

```
~ $ git clone -b High-Tune-0.6.1 \
    https://gitlab.com/meso-star/star-engine.git High-Tune-0.6.1
~ $ mkdir High-Tune-0.6.1/build; cd High-Tune-0.6.1/build
~/High-Tune-0.6.1/build $ cmake ../cmake
~/High-Tune-0.6.1/build $ make
```

Install htspk

```
~ $ wget https://www.meso-star.com/projects/high-tune/downloads/\
    High-Tune-Starter-Pack-0.6.0.tar.gz
~ $ tar xzvf High-Tune-Starter-Pack-0.6.0.tar.gz
```

Setup the working environment

Register `htrdr` against the current GNU/Bash shell

```
~ $ source ~/High-Tune-0.6.1/local/etc/high_tune.profile
~ $ htrdr -h
~ $ man htrdr
~ $ export HTSPK=~/High-Tune-Starter-Pack-0.6.0
```

Create the working directory

```
~ $ mkdir Tuto
~ $ cd Tuto
~/Tuto $ echo "Hello, world!"
```

Clear sky rendering

First rendering

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/plane.mtls \
  -g $HTSPK/models/plane.obj -R \
  -i def=640x480:spp=128 \
  -C pos=0,0,100:tgt=0,1,100 \
  -o clear_sky.txt
```

Display the rendered image

```
~/Tuto $ htpp -h
~/Tuto $ man htpp
~/Tuto $ htpp clear_sky.txt | display -
~/Tuto $ htpp -o clear_sky.ppm clear_sky.txt
~/Tuto $ display clear_sky.ppm
~/Tuto $ htpp -i exposure=0.2 -o clear_sky_0.2.ppm clear_sky.txt
~/Tuto $ display clear_sky.ppm clear_sky_0.2.ppm
```

Overwrite the default sun position

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/plane.mtls \
  -g $HTSPK/models/plane.obj -R \
  -i def=640x480:spp=128 \
  -C pos=0,0,100:tgt=0,1,100 \
  -D 90,20 \
  -o clear_sky.txt -f

~/Tuto $ htpp -i exposure=0.2 clear_sky.txt | display -
```

Update the camera

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/plane.mtls \
  -g $HTSPK/models/plane.obj -R \
  -i def=640x480:spp=128 \
  -C pos=0,0,100:tgt=0,1,100.5:up=0,0,1:fov=60 \
  -D 90,20 \
  -o clear_sky.txt -f

~/Tuto $ htpp -i exposure=0.2 clear_sky.txt | display -
```

Cloud field rendering

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/plane.mtls \
  -g $HTSPK/models/plane.obj -R \
  -i def=640x480:spp=4 \
  -C pos=0,0,100:tgt=0,1,100.5:up=0,0,1:fov=60 \
  -D 90,20 \
  -m $HTSPK/Mie_LUT_Cloud-2-10-0.010.nc \
  -c $HTSPK/clouds/DZVAR.1.ARMCU.008.diaKCL.htcp \
  -O DZVAR_octrees.cache \
  -o sky_DZVAR.txt

~/Tuto $ htpp -i exposure=0.2 sky_DZVAR.txt | display -
```

Infinitly repeat the clouds

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/plane.mtls \
  -g $HTSPK/models/plane.obj -R \
  -i def=640x480:spp=4 \
  -C pos=0,0,100:tgt=0,1,100.5:up=0,0,1:fov=60 \
  -D 90,20 \
  -m $HTSPK/Mie_LUT_Cloud-2-10-0.010.nc \
  -c $HTSPK/clouds/DZVAR.1.ARMCU.008.diaKCL.htcp -r \
  -O DZVAR_octrees.cache \
  -o sky_DZVAR.txt -f

~/Tuto $ htpp -i exposure=0.2 sky_DZVAR.txt | display -
```

Dump the octrees

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/plane.mtls \
  -g $HTSPK/models/plane.obj \
  -m $HTSPK/Mie_LUT_Cloud-2-10-0.010.nc \
  -c $HTSPK/clouds/DZVAR.1.ARMCU.008.diaKCL.htcp \
  -O DZVAR_octrees.cache \
  -d \
  -o octrees.txt

~/Tuto $ csplit \
  -f cloud_octree_ \
  -b %02d.vtk \
  -z \
  --suppress-matched \
  octrees.txt \
  /^---$/ *

~/Tuto $ paraview cloud_octree_11.vtk
```

Update the optical thickness criterion

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/plane.mtls \
  -g $HTSPK/models/plane.obj -R \
  -i def=640x480:spp=4 \
  -C pos=0,0,100:tgt=0,1,100.5:up=0,0,1:fov=60 \
  -D 90,20 \
  -m $HTSPK/Mie_LUT_Cloud-2-10-0.010.nc \
  -c $HTSPK/clouds/DZVAR.1.ARMCU.008.diaKCL.htcp -r \
  -T 0.01 \
  -O DZVAR_octrees_0.01.cache \
  -o sky_DZVAR_0.01.txt

~/Tuto $ htpp -i exposure=0.2 sky_DZVAR_0.01.txt | display -
```

Update the ground surface

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/mountain.mtls \
  -g $HTSPK/models/mountain.obj -R \
  -i def=640x480:spp=4 \
  -C pos=0,0,600:tgt=0,1,600.1:up=0,0,1:fov=60 \
  -D 90,60 \
  -m $HTSPK/Mie_LUT_Cloud-2-10-0.010.nc \
  -c $HTSPK/clouds/DZVAR.1.ARMCU.008.diaKCL.htcp -r \
  -O DZVAR_octrees.cache \
  -o sky_DZVAR_mountain.txt

~/Tuto $ htpp -i exposure=0.2 sky_DZVAR_mountain.txt | display -
```

Infrared rendering

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/mountain.mtls \
  -g $HTSPK/models/mountain.obj -R \
  -i def=640x480:spp=128 \
  -C pos=0,0,600:tgt=0,1,600.1:up=0,0,1:fov=60 \
  -D 90,60 \
  -m $HTSPK/Mie_LUT_Cloud-2-10-0.010.nc \
  -c $HTSPK/clouds/DZVAR.1.ARMCU.008.diaKCL.htcp -r \
  -s lw=9000,10000:Tref=590 \
  -O DZVAR_octrees_lw_9000nm_10000nm_590K.cache \
  -o sky_DZVAR_mountain_lw.txt
```

Display heat map

Display expected value

```
~/Tuto $ htpp -v -m pixcpnt=0 sky_DZVAR_mountain_lw.txt | display -
~/Tuto $ htpp -v -m pixcpnt=0:gnuplot -o heat_map.gp sky_DZVAR_mountain_lw.txt
~/Tuto $ gnuplot heat_map.gp > heat_map.png
~/Tuto $ display heat_map.png
```

Display standard error

```
~/Tuto $ htpp -v -m pixcpnt=1:gnuplot sky_DZVAR_mountain_lw.txt | gnuplot - | display -
```

Computing ascending flux in longwave

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/plane.mtls \
  -g $HTSPK/models/plane.obj -R \
  -i def=512x512:spp=128 \
  -D 0,90 \
  -m $HTSPK/Mie_LUT_Cloud-2-10-0.010.nc \
  -c $HTSPK/clouds/DZVAR.1.ARMCU.008.diaKCL.htcp -r \
  -s lw=4000,10000 \
  -O DZVAR_octrees_lw_4000nm_10000nm.cache \
  -p pos=3200,3200,80000:tgt=3200,3200,0:up=0,1,0:sz=6400,6400 \
  -o sky_DZVAR_plane_lw_ascending_flux.txt

~/Tuto $ htpp -v -m default sky_DZVAR_plane_lw_ascending_flux.txt | display -
```

Computing descending flux in longwave

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/plane.mtls \
  -g $HTSPK/models/plane.obj -R \
  -i def=512x512:spp=128 \
  -D 0,90 \
  -m $HTSPK/Mie_LUT_Cloud-2-10-0.010.nc \
  -c $HTSPK/clouds/DZVAR.1.ARMCU.008.diaKCL.htcp -r \
  -s lw=4000,10000 \
  -O DZVAR_octrees_lw_4000nm_10000nm.cache \
  -p pos=3200,3200,1:tgt=3200,3200,2:up=0,1,0:sz=6400,6400 \
  -o sky_DZVAR_plane_lw_descending_flux.txt

~/Tuto $ htpp -v -m default sky_DZVAR_plane_lw_descending_flux.txt | display -
```

Computing descending flux in shortwave

```
~/Tuto $ htrdr -v \
  -a $HTSPK/ecrad_opt_prop.txt \
  -M $HTSPK/materials/plane.mtls \
  -g $HTSPK/models/plane.obj -R \
  -i def=512x512:spp=32 \
  -D 0,90 \
  -m $HTSPK/Mie_LUT_Cloud-2-10-0.010.nc \
  -c $HTSPK/clouds/DZVAR.1.ARMCU.008.diaKCL.htcp -r \
  -s sw=380,780 \
  -O DZVAR_octrees_sw_380nm_780m.cache \
  -p pos=3200,3200,1:tgt=3200,3200,2:up=0,1,0:sz=6400,6400 \
  -o sky_DZVAR_plane_sw_descending_flux.txt

~/Tuto $ htpp -v -m range=0,900 sky_DZVAR_plane_sw_descending_flux.txt | display -
```

The `ht-run.sh` GNU/Bash script

Build a `htrdr` command line from an input file that describes the scene to render

```
~/Tuto $ cat $HTSPK/scenes/city
~/Tuto $ cat $HTSPK/ht-run.sh | more
~/Tuto $ bash $HTSPK/ht-run.sh $HTSPK/scenes/city
~/Tuto $ htpp -i exposure=0.2 city_1280x720x256.txt | display -
```