

A program for processing digital hemispherical images

***HSP***

***HemiSPherical Project Manager***

***ver: 1.3.3***

user manual

Mait Lang

Tõravere 09.04.2014

# Content

Introduction.....	3
Licence conditions .....	4
Hemispherical images for canopy gap fraction measurements.....	5
HSP installation and setup.....	7
Image processing with HSP.....	7
Basic principles.....	7
Importing images from raw data files into projects.....	8
How to use ddraw.....	8
Camera profiles.....	9
Restoration of the above canopy image.....	11
The list of images.....	11
Image display and markup.....	12
Interpolation and model settings for above canopy image restoration.....	14
Calculation of gap fraction and export of the results.....	18
Some practical recommendations.....	19
Acknowledgements.....	19
References.....	20

## Introduction

The amount of green leaves conducting photosynthesis is one of the most important variables in plant canopies. To describe the amount of leaves, leaf area index (LAI) was defined by Watson (1947) as the total one sided area of leaf tissue per unit ground surface area. The value of LAI depends on definition of leaf or needle area (Sellin, 2001; Flower-Ellis and Olsson, 1993). Half of total area is usually used for flat leaves and projection area is used for needles.

A long list of methods for LAI measurements and estimation exists, the list ranging from remote sensing from satellites to the destructive sampling methods (Jonckheere *et al.*, 2004; Kodar *et al.*, 2008). One popular method is based on inversion of canopy gap fraction data obtained from plant canopy analyzers or from hemispherical images. In case of plant canopy analyzers e.g. LAI-2000, data from two sensors are used: one reference device is measuring the incident radiation of unobscured sky  $I_0$  in an open area and second device measures the penetrated radiation below canopy  $I$ . The ratio  $T=I/I_0$  is canopy transmittance and if measured in the blue spectral region where sky is bright and plant elements are black (assumed as not transmitting and not reflecting) then  $T$  is equal to the canopy gap fraction.

There are many software applications available to estimate canopy gap fraction from hemispherical images (Walter, 2009; Weiss, 2013; Frazer *et al.*, 1999). All the applications are using subjective decision of image interpreter to classify pixels into sky and plant classes based on separating pixels by their value (thresholding) or selecting pixels by colors (Jonckheere *et al.* 2005). The unsolved issue of the subjective decision and impact of camera settings on the gap fraction and, hence, LAI estimation is discussed by many authors (Rich, 1990; Macfarlane *et al.*, 2000; Hale and Edwards, 2002; Inoue *et al.*, 2004; Leblanc *et al.*, 2005; ; Zhang *et al.*, 2005; Chianucci and Cutini, 2012).

The HSP software implements new approach to measure canopy gap fraction by using a linear conversion of digital hemispherical images as proposed by Cescatti (2007) where the above canopy reference measurements are restored from below canopy images according to Lang *et al.* (2010). The solution is almost independent from operator subjectivity and relies on the capability of the modern digital cameras to store unprocessed sensor readings (*raw data*) in addition to common *tiff* or *jpeg* images.

## Licence conditions

HSP - HemiSPherical Project Manager is a freeware and licenced under the Apache 2.0 licence (<http://www.apache.org/licenses/LICENSE-2.0.html>).

Copyright 2012, Mait Lang.

Licensed under the Apache License, Version 2.0 (the "License");  
you may not use this file except in compliance with the License.  
You may obtain a copy of the License at

<http://www.apache.org/licenses/LICENSE-2.0>.

Unless required by applicable law or agreed to in writing, software  
distributed under the License is distributed on an "AS IS" BASIS, WITHOUT  
WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied. See the  
License for the specific language governing permissions and limitations  
under the License.

Some of the third party libraries used in HSP are licenced under the BSD licence.

### *Referencing*

The method is published in

Lang, M., Kuusk, A., Mõttus, M., Rautiainen, M., and Nilson, T. 2010. Canopy gap fraction estimation from digital hemispherical images using sky radiance models and a linear conversion method. *Agricultural and Forest Meteorology*, 150(1), 20-29.

HemiSPherical Project Manager software

Lang, M., Kodar, A., Arumäe, T. 2014. Restoration of above canopy reference hemispherical image from below canopy measurements for plant area index estimation in forests. Submitted to *Forestry Studies*.

## Hemispherical images for canopy gap fraction measurements

The regular customer grade digital cameras are not measurement devices but designed to produce the most native looking pictures for human vision. The CCD or CMOS sensors of the cameras register incident light and output a signal which is linearly dependent on the incident light power. Each detector of such sensors has a particular color filter (Figure 1a). The most widespread filter pattern has three basic colors - red green, blue (RGB). To create a picture for human vision the color information is interpolated, and several nonlinear adjustments including gamma correction are applied to the image data (Figure 1b,c). All these processing steps introduce noise and errors if the image data are intended for canopy gap fraction measurements.

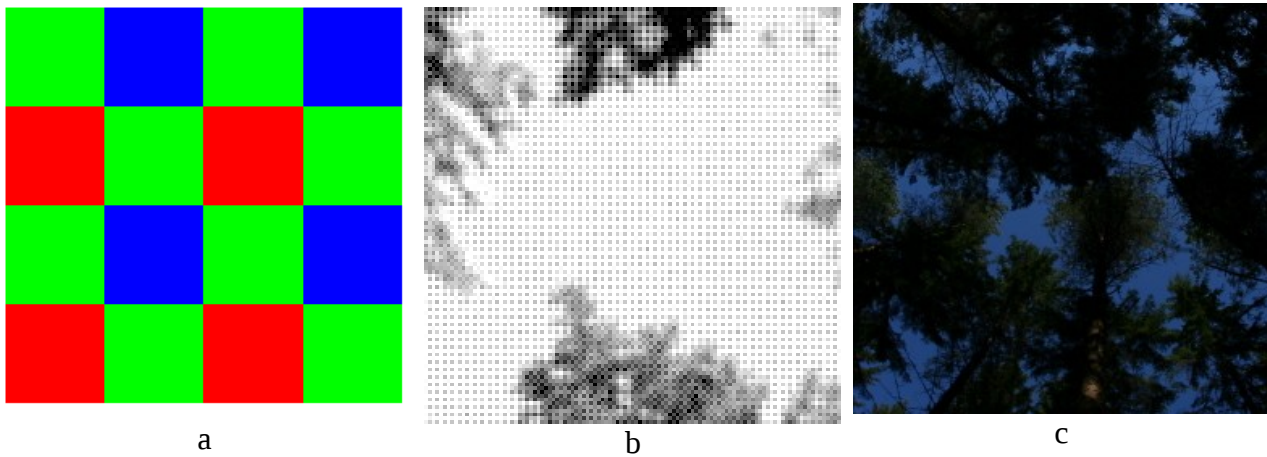


Figure 1. Each pixel in digital camera sensor has a particular color filter (a); a sample of the raw data from sensor before color signal interpolation (b); the regular color image after color interpolation and gamma correction (c).

For LAI estimation from canopy transmittance measurements the foliage is assumed to be opaque and not reflecting. These assumptions are almost fulfilled in the blue spectral region where the signal can also be measured with digital cameras. Only those pixels with original blue filter are in interest (Figure 1a), since interpolated values over the pixels with green and red filters do not contain any new information. The necessary data for canopy transmittance calculation are stored as *raw data* files by many cameras.

Special lenses capable to capture an image from hemisphere are used to measure angular dependence of canopy gap fraction. The field of view of such (fisheye) lenses ranges often even below the horizon (Figure 2). The image of hemisphere is projected onto camera sensor and in an ideal case the distance  $d$  (in pixels) from the image center would be linearly proportional to the view zenith angle  $\theta$ . To extract the hemispherical image one needs to know the center coordinates of the projection ( $X_p, Y_p$ ) and the distance  $d$  corresponding to  $\theta=90^\circ$ . The real optical systems consisting of hemispherical lens and digital camera have at least two types of distortions: 1) projection is not linear and 2) due to vignetting an object with constant brightness is darker at larger values of  $\theta$  (Figure 3). The projection distortion and vignetting are measured in radiometry lab and corresponding correction models can be applied (Lang *et al.* 2010).



Figure 2. An hemispherical image taken with leveled camera from tripod. The field of view extends below horizon. The direct radiation from the Sun is screened to avoid artifacts due to significant scattering in the optical system.

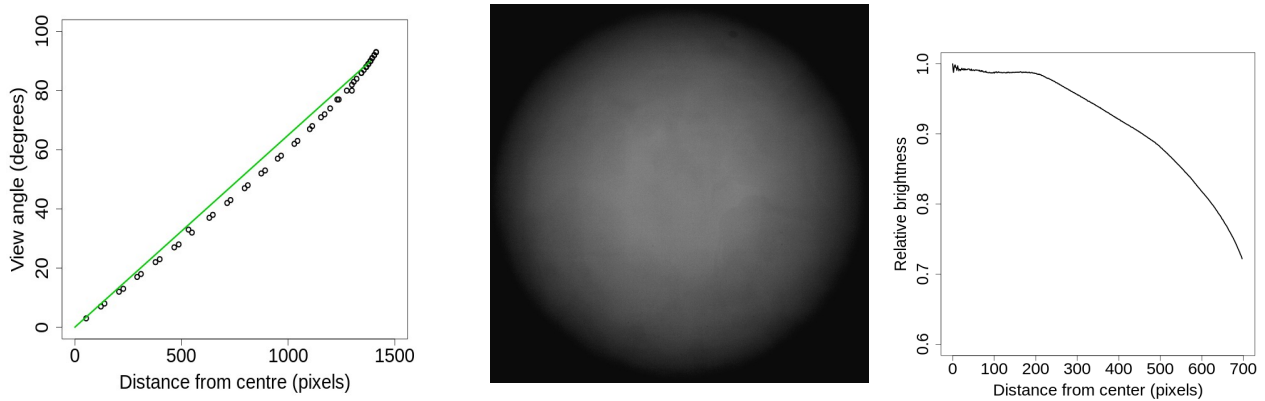


Figure 3. In the real optical systems the projection of the hemisphere onto sensor is usually not linear (a). Due to lens and camera vignetting an object with constant brightness looks darker at the larger view angles. The vignetting can be measured in a photometric sphere (b, c).

The hemispherical images for canopy gap fraction measurements must be made with diffuse illumination which occurs after sunset or before sunrise or during overcast (Welles and Normann, 1991). For practical reasons so-called local cloud shading method is sometimes used when a cloud shades the canopy to be measured from direct sunlight. Compared to plant canopy analyzers e.g. LAI-2000, digital cameras are not designed to be used as measurement devices. To avoid over- and underexposure (too small signal range or saturation) the camera operator has to adjust sensor sensitivity (ISO), shutter speed and lens aperture. Most of the modern digital cameras can display image histogram which can be used as a guideline to keep the maximum values of pixels in image in the range of 25%-70% of the sensor's maximum output value.

## HSP installation and setup

The HemiSpherical Project Manager is written in Java and needs Java environment. For installation: create a folder HSP and unzip the archive containing the HSP.jar and its libraries. Depending on operating system, special rights for user may be required - consult respective documentation for Java and the operation system. There are no special requirements for computer hardware, however, it is recommended to have more than 1GB free RAM, mouse and free space on hard disk (data storage) for data.

The HSP does not have procedures to read data from camera specific raw data files, but relies on free utility *dcraw* (Coffin 2013). The *dcraw* is a command line program run in cmd (windows) or xterm (linux) or other terminal emulators depending on computer operating system. For HSP the location of *dcraw* must be defined later in *Preferences* menu.

The HSP can be executed by clicking on the HSP.jar (success depends on operating system settings) or preferably from command line by executing: `java -jar HSP.jar`. It is recommended to extend available memory for the HSP by adding switch `-Xmx512m` (or even `-Xmx1024m`). Consult documentation of your computer operating system about how to create batch files for HSP execution.

Setup for HSP is done in *Preferences* menu. Here the location of *dcraw* executable is indicated and the main working folder (*root directory*) is selected. The root directory will contain all the files related to the processing of hemispherical images. The user must have write access to the location of the root directory, the name and location of the root directory can be freely selected. It is recommended to avoid spaces in the file and folder names. Restart HSP after changing the root directory.

The HSP root directory contains following folders (created automatically):

1. **Camera configurations** – files with camera and lens descriptions including vignetting and projection models;
2. **Palettes** – color pallets for image display;
3. **Projects** – contains the hemispherical images and all files related to data processing;
4. **Sky models** – standard models of sky brightness (CIE 2004, Kittler 1994).

Examples of camera configuration files and of the sky models are not included with HSP.jar and must be downloaded separately.

## Image processing with HSP

### ***Basic principles***

The images are handled as groups and for each group HSP creates a named folder under **Projects** directory. It is up to user do decide if a project contains only a single image or several images from a sample plot. A hint here is that HSP can calculate average gap fraction over all images in a project. Projects can be created from HSP main menu *File\ New project*.

Image processing is carried out in three steps:

- 1) image import from camera specific raw data files, extraction of pixels with blue filter, correction for projection distortions and vignetting, and resampling images into specified size;
- 2) image markup and restoration of above canopy reference image;
- 3) canopy gap fraction calculation and export of results.

### **Importing images from raw data files into projects**

To import hemispherical images from *raw data* files:

- 1) Add references to image files (Figure 4);
- 2) Select images and assign/create camera description, insert *dcraw* switches and select dark frame image;
- 3) run image import with *<Calibrate>* button.

User has an option to group images within each project for better overview. This option is useful in case when different cameras were used to make images in the same sample plot. Assign a group label before other settings. Run calibration for each group individually.

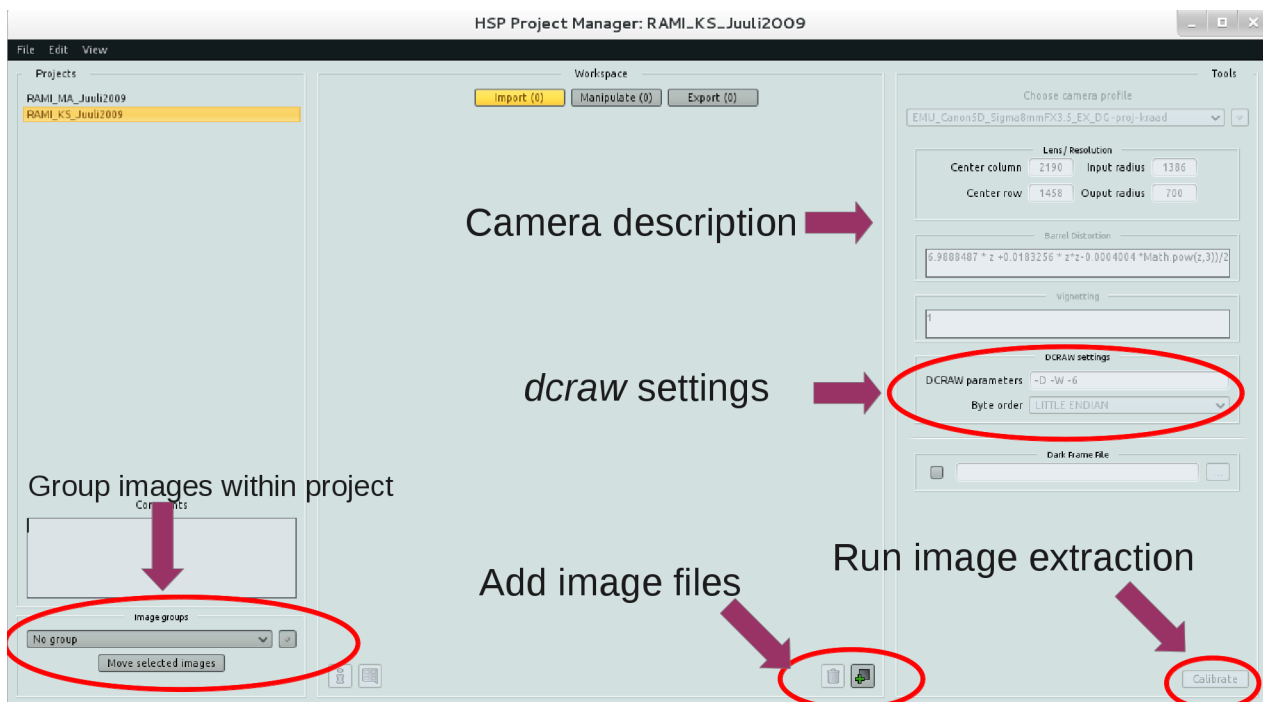


Figure 4. Image processing begins with adding references to raw data files into the project. Then the corresponding camera profile is created or selected and all other setting are to be fixed before image extraction from raw data files.



## How to use *dcrw*

HSP calls *dcrw* with given switches to extract images from camera specific *raw data* files. The user is fully responsible to test the *dcrw* version functionality and switches before image analysis for each particular camera, and determine the appropriate switches. After updating *dcrw*, run tests with some images to detect any differences in the output *pgm* files compared to previous results. Some general recommendations can be given. It is important to switch off interpolation and preferably any scaling when extracting images from *raw data* files. For some cameras the subtraction of dark frame images is required.

To extract images from camera specific data files one can use following switches with *dcrw* version 9.17:

- D *Document mode without scaling (totally raw);*
- W *Don't automatically brighten the image;*
- 6 *Write 16-bit instead of 8-bit.;*
- g 1 1 *does not apply gamma correction.*

It is possible to use an integrated switch (add -D):

- 4 *Linear 16-bit, same as "-6 -W -g 1 1".*

If *dcrw* is used independently outside HSP (for example to prepare data for camera calibration) then for some cameras dark current images (taken with optics fully covered) must be subtracted from useful signal by using:

- K <file> *(Subtract dark frame (16-bit raw PGM)).*

The dark frame images represent sensor noise and bias data. Take the dark frame images when camera body temperature has stabilized. Tests have shown the dark current signal for Canon EOS 5D is about 128 DN (digital numbers), but only 3-4DN for Nikon CoolPix 4500.

In HSP, the -K switch is added automatically and the dark image is converted automatically if corresponding file is indicated (Figure 4). The dark image file name is stored after user presses <Calibrate> button for selected images.

## Camera profiles

HSP requires auxiliary information to extract hemispherical image from pixel array. This information includes image projection model, vignetting model; hemispherical image location and size in the pixel array. All this information can be stored as a named camera profile.

The location and size of an hemispherical image in the pixel array extracted by *dcrw* from *raw data* files is given by the image *Center column*, *Center row*, and *Input radius* ( $r_{inp}$ , pixels), corresponding to the 90 degrees view zenith angle. Images from different cameras can be resampled into the same size by determining *Output radius*  $r_{out}$  value. For example if  $r_{inp} = 1386$  then set  $r_{out} = 1400$ . These values must be given for the matrix containing all pixels (the file produced by *dcrw* -D -4 <raw data file>).

During the image import HSP asks *dcrw* to extract the camera sensor filter pattern string from *raw data* files and picks only the pixels with blue filter. As a result the number of the image columns and rows will be reduced by the factor of two.

The image projection and vignetting models can be input as mathematical equations. User can call functions from java library *Math*, e.g  $Math.\ln(d)$ ,  $Math.PI$  (see Javadoc, 2012). HSP internal

variables can be used to refer to shutter speed  $Sh$  , aperture  $Ap$  and focal length  $Fl$  values read for each image from EXIF data.

If the projection and vignetting models are not known then default values corresponding to an ideal camera can be used. The image projection model relates its pixel distance from image centre  $d$  to view zenith angle  $\theta$  . The simplest projection model is  $d=2\theta r_{inp}/\pi$  where  $\theta$  is in radians. **In the present HSP version the projection model is applied to the image created of blue pixels. Thus, a factor 0.5 must be applied and the previous simple linear projection model must be input in HSP as  $d=\theta r_{inp}/\pi$  .**

The image projection model can be derived from measurements made in a radiometry lab. For example, a Canon EOS 5D with Sigma 8mm F3.5 EX DG was calibrated in Tartu Observatory radiometry lab (Lang *et al.*. 2010) and the projection model for the camera

$$d=973.389\theta+60.160\theta^2-75.316\theta^3 \quad (1)$$

is input in HSP as  $0.5*(973.389*z+60.160*Math.pow(z,2)-75.316*Math.pow(z,3))$  where  $z$  is HSP variable for  $\theta$  , 0.5 accounts for extraction of blue pixels and  $Math.pow()$  is the power function from java Math library. The decimal separator may depend on operating system and settings and can be comma or point.

The measurements for determining projection model for a camera do not require special equipment but for measurements of vignetting a sufficiently large photometric sphere is needed. The vignetting model in HSP predicts relative brightness of a pixel  $B_\theta$  at view zenith angle  $\theta$  in respect to zenith brightness  $B_{\theta=0}$  . If the vignetting model is not known then constant value  $B_\theta=1$  must be used. For example, vignetting model for Sigma 8mm F3.5 EX DG mounted on Canon EOS 5D camera was created using measurements made in Tartu Observatory and the model accounts for view zenith angle  $\theta$  and aperture number  $A$  (Lang *et al.*, 2010)

$$B_\theta=0.8260719-\frac{91.8757553\theta}{A^{4.6077200}}+0.0568885\ln((24.3614701-A)(1.6-\theta)) \quad (2)$$

The vignetting model (2) parameters are specific to the particular camera and lens.

### Some notes and hints

It is recommended to experiment with *dcraw*, since there can be some unexpected differences in image extraction process depending on operation system and *dcraw* version.

Select an image in HSP and press *Space* key on keyboard to display EXIF data.

Select an image or images, fix all required settings and then press *<Calibrate>* to start data import.

Selecting of images from the image list can be done with mouse and keyboard. *SHIFT+MouseLeft* selects individual images, *CTRL+A* selects all images within group. To select images from different groups combine *CTRL+SHIFT +MouseLeft*. The combinations may depend on operating system and settings.

## Above canopy image restoration

To calculate canopy gap fraction the data of incident radiation above  $I_0$  and below the canopy  $I$  are required. HSP relies on assumption that the digital numbers in *raw data* files are linearly related to the incident radiation power, thus the above canopy hemispherical image can be restored by using samples taken from canopy gaps (Lang *et al.*, 2010). The  $I_0$  image can be created by using interpolation or a mathematical model of sky radiation distribution or by combination of both methods. The interpolation procedure as well as sky radiation distribution model require the user to place marks on image to take samples of sky pixels.

## The list of images

All the hemispherical images for which the  $I_0$  image can be created are located on the *Manipulate* page in HSP main window (Figure 5).

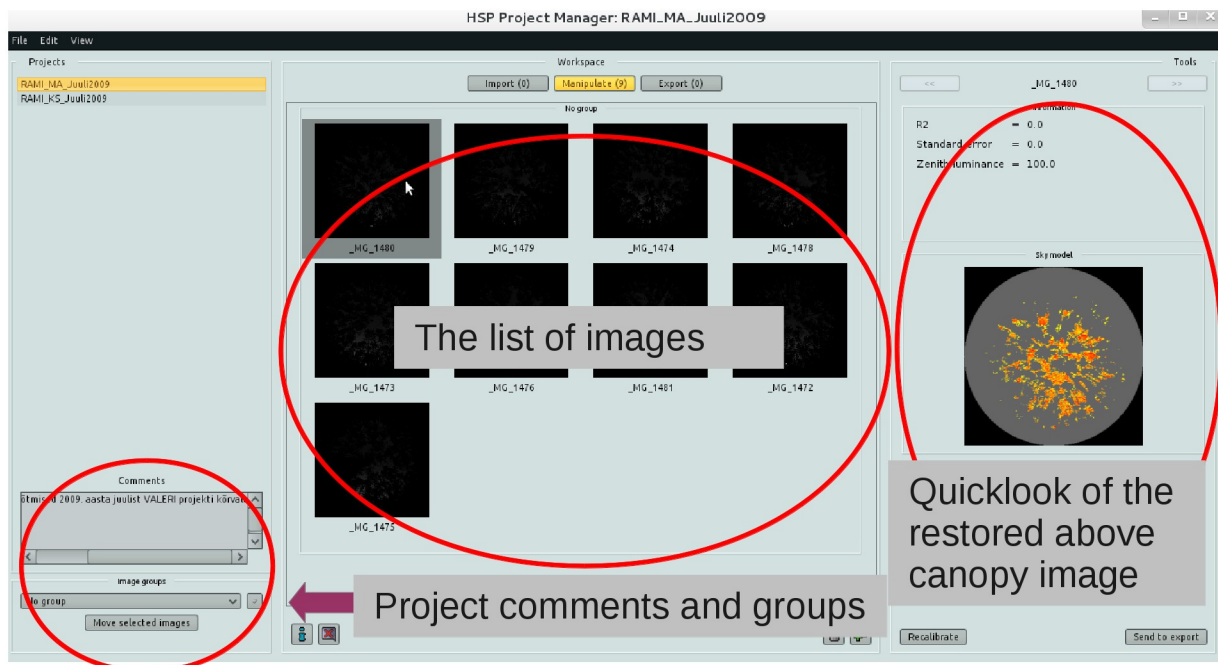


Figure 5. The list of images for above canopy image restoration and the list management tools.

**WARNING: If images are sent back to calibration for a some reason with <Recalibrate>, then all the sky marks and associated data will be erased. Make backup copy of \*.conf files found in the “manipulate” folder under project directory before sending images back to calibration. The old \*.conf files are valid only if the projection model and the image size ( $r_{ou}$ ) are not changed.**

## Image display and markup

To start image markup for sky pixel sampling doubleclick on an image in the list (Figure 5). Several tools are available in the markup panel (*Markup*) and above canopy image restoration panel (*Sky model*).

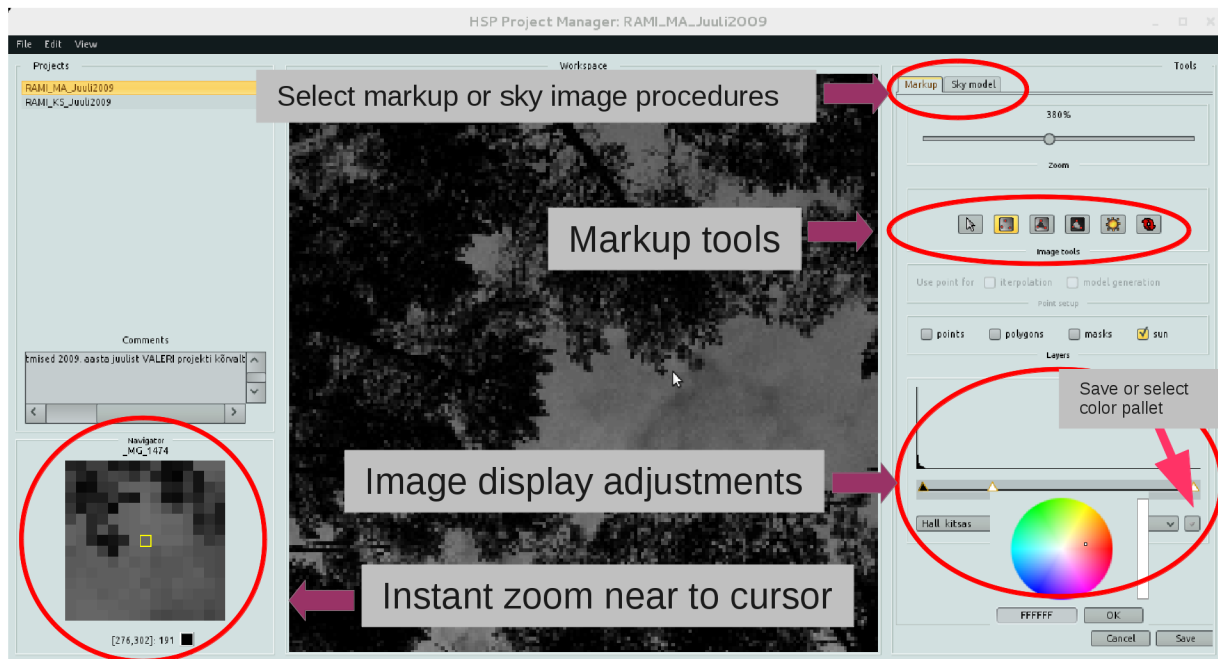


Figure 6. The tools for image display adjustment, image markup and above canopy sky image restoration.

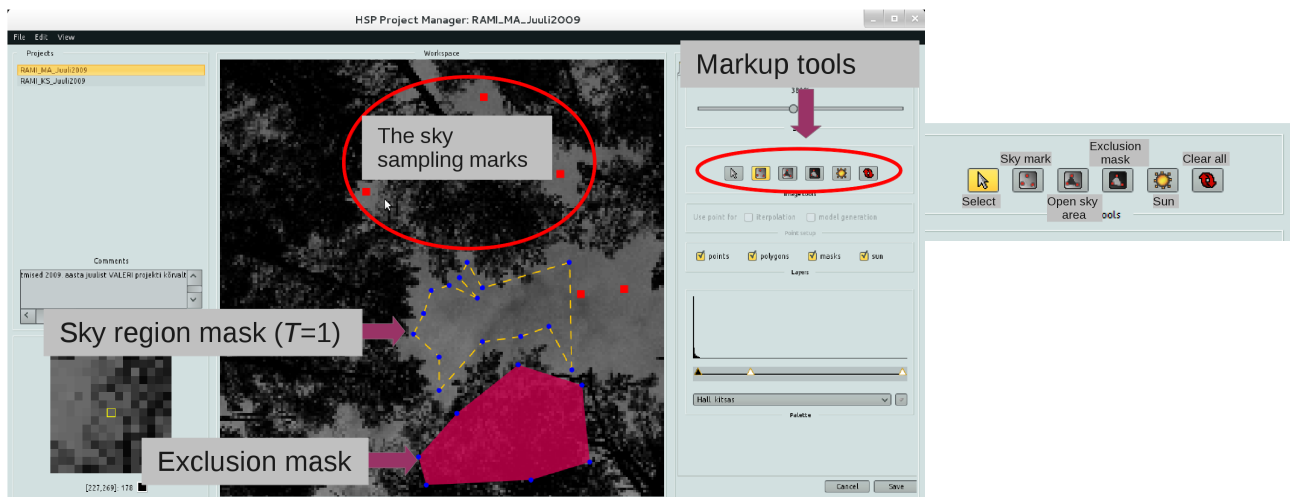


Figure 7. Image markup tools allow placing open sky marks, delineate larger open sky areas, indicate exclusion of pixels from gap fraction calculation and allow setting position of sun. Cursor coordinates (column and row) pixel value below cursor are shown left below the Navigator window.

User can adjust image display settings for visual interpretation - this does not influence the data. It

is recommended to avoid too strong contrast enhancement, since small gaps of mixed pixels can be then wrong interpreted as unobscured sky. The image display can be adjusted by the sliding triangular buttons below the histogram (Figure 7). Doubleclick on the button opens color selection menu. Right click on color button deletes it. New color pallets can be created and changes can be saved for further use.

Image can be zoomed with *PageUp*, *PageDown* or mouse wheel (applies to touchpads with wheel emulator too). Image can be moved with arrows or by grabbing with *RightMouse*.

Image markup starts with selecting corresponding function for mouse (Figure 7). The position of sun can be changed, the mark can not be removed. User can add and delete (keyboard *Del*) open sky markers. The position of existing open sky markers can not be changed. Each sky marker can serve as a point to sample data for interpolation or for mathematical model or for both. This options may be useful for outlier points which complicate fitting of the mathematical model on sky sample data.

Two types of masks are available. Larger open sky areas can be delineated with sky masks. If the masks are included in gap fraction calculation then all the image pixels within sky area mask are assigned  $T=1.0$ . The second type of mask is for excluding pixels from analysis. Each mask polygon must be digitized in one sequence. The polygon vertices can be moved but not deleted. Deleting removes the entire mask polygon. To select sky markers or mask polygons for deleting hold down *SHIFT+LeftMouse* and drag cursor over the objects. Check the selection before pressing *Del*. **There are no options for Undo.**

Sky masks have an extra functionality. HSP can display histogram of the estimated gap fraction values for the pixels under the selected open sky mask polygons. This feedback is useful, since the average transmittance of an open sky area must be close to  $T=1.0$  if the above canopy image restoration is successful.

User can display a circle to mark the near zenith area (*MAZ*) which is used to select samples for zenith pixel brightness estimation. The near zenith area marker is painted during initialization of the image markup. Save data and start the markup again to refresh near zenith area marker display after changing *MAZ* value.

### **Recommendations and notes**

Mark sun position first even if the sky is overcast with clouds, since the position of sun is used in CIE model (CIE, 2004; Kittler, 1994) fitting.

Place the open sky markers uniformly over the image. Near zenith markers are important. To fit CIE model on an image the minimum number of sky markers must be at about 20. The sky radiance is sampled from 3x3 pixel window around each sky marker, hence the gap must be at least 5x5 pixels to avoid mixed pixels. Deciding about markers at larger view zenith angles requires some practicing, since gaps in canopy become smaller.

The mouse function is not automatically changed to “*Select*” if the *Markup* panel is inactivated and the last markup function remains active for mouse. Be prepared for occasional false sky markers if executing *LeftMouseClicked* upon the image area when, for example, the *Sky model* panel is activated for adjusting interpolation or model settings.

### **Interpolation and model settings for above canopy image restoration**

The basic criterion for validation of the above canopy reference image restoration is straightforward: the pixels in the canopy gaps must have transmittance close to  $T=1$  and transmittance of the tree stems must be close to  $T=0$ . There are many possible error sources for gap fraction calculation - sensor noise, variability of sky radiance, artifacts due to interpolation, misplaced sky markers, wrong parameter values used for sky model, etc.

The above canopy image can be restored from below canopy image by:

- 1) inverse distance weighted interpolation of open sky samples;
- 2) using a standard sky model from CIE (CIE, 2004) or previously saved model;
- 3) fitting the CIE model parameters  $a..e$  on the open sky samples taken from the image;
- 4) mixing the methods 1 and 3 to account for local variability and account for systematic trends in sky radiation.

For interpolation determine 1) the number of near sky markers  $MP$  to be used for pixels, and 2) the maximum search radius  $PR$  (in pixels) of the near-by sky markers. For mathematical model, determine the near zenith region for zenith pixel value estimation  $MAZ$  (degrees). It is possible to input the zenith pixel value  $ZL$  manually (Figure 8).

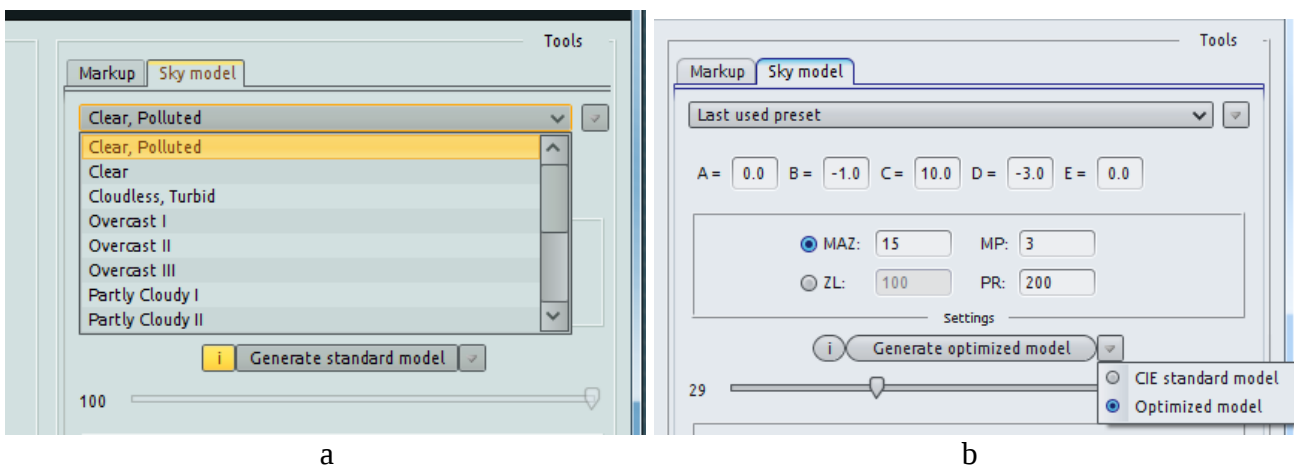


Figure 8. Selection of the above canopy image restoration method and settings. User can select a standard or saved model (a, b), fit sky model on the image data or use interpolation (Optimized model) (b).

**A note:** The CIE model requires value of zenith pixel (CIE, 2004; Kittler, 1994). If camera is intentionally placed below the canopy gaps then the canopy cover and LAI estimates will be biased. Thus, the samples from the near zenith gaps must be used to estimate the zenith pixel value. If possible, then place at least three open sky markers into the near zenith area determined by the  $MAZ$ . Keep the  $MAZ$  as small as possible, since sky brightness changes systematically and asymmetrically with increasing the view zenith angle.

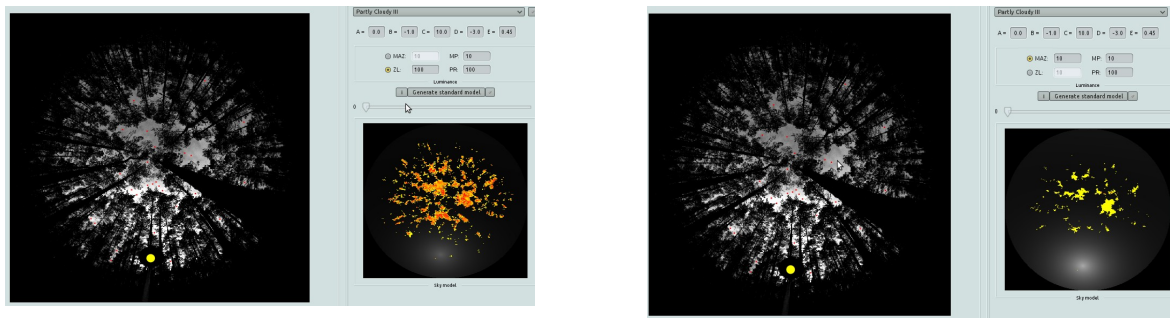


Figure 9. An example of canopy gap fraction estimation in case of using a CIE standard sky model with a) a manually input zenith pixel value; b) zenith pixel value estimated from near zenith open sky markers. Orange color indicates  $T > 1.15$  (positive bias) and yellow corresponds to  $1.05 \leq T \leq 1.15$ .

The CIE (2004) standard models are useful as starting points to study the images. The notes made during fieldwork or an expert guess helps to select appropriate model (i.e. values for parameters  $a..e$ ). However, the standard cases do hardly occur in real measurement situations. The required zenith brightness value for CIE model can be input manually ( $ZL$ ) or preferably calculated from the below canopy image (Figure 9).

Interpolation can be considered as the optimal solution for above canopy sky image restoration. The number of samples ( $MP$ ) used in the interpolation can range from 1 to 10. Usually the  $MP=3$  is a good choice. The search range of sky sample ( $PR$ ) value has impact on the interpolation procedure. In case of few sample points and small  $PR$ , far pixels will be assigned the “Exclude” flag (Figure 10). The recommended value for  $PR$  is about 15 to 20 degrees.

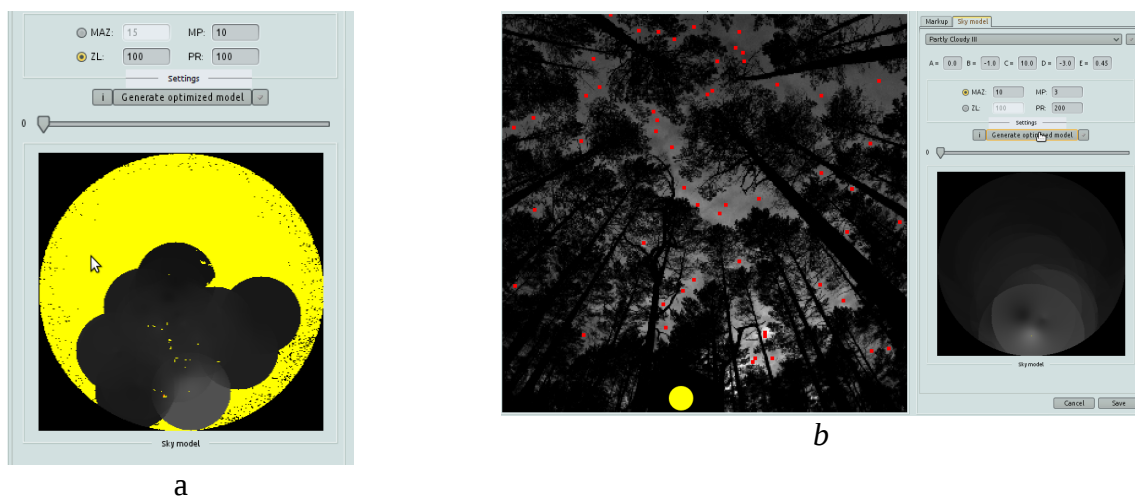


Figure 10. Interpolation procedure requires determination the number of samples and the sample search distance. a) For the large yellow area the samples were not found. b) The above canopy image was restored in full extent.

The CIE model parameters can be fitted on the sky sample data to predict the above canopy radiance for each pixel. The result depends somewhat on the initial solution, on the number and location of sky samples, and on the position of sun mark. Standard parameter sets of the CIE model serve as initial solutions for fitting the model on the image. The NelderMeadSimplex procedure



from class `org.apache.commons.math3.optimization.direct.NelderMeadSimplex` from Apache Commons Math package is used in the HSP for model fitting.

The sky samples must be distributed uniformly over the image as much as possible. It is important to assess the concordance of the fitted model to the field observations. The probability of finding sufficiently large gaps to sample for sky pixel values decreases with increasing of view zenith angle. For example, the lack of observations can result in a fitted model that predicts increase of the overcast sky brightness towards horizon (Figure 11), which is not realistic. On the other hand, the increase of clear sky brightness towards horizon is a rule. The mathematical model can have locally large residual errors. Thus, the image interpreter has to select appropriate balance between the model and interpolation (Figure 12).

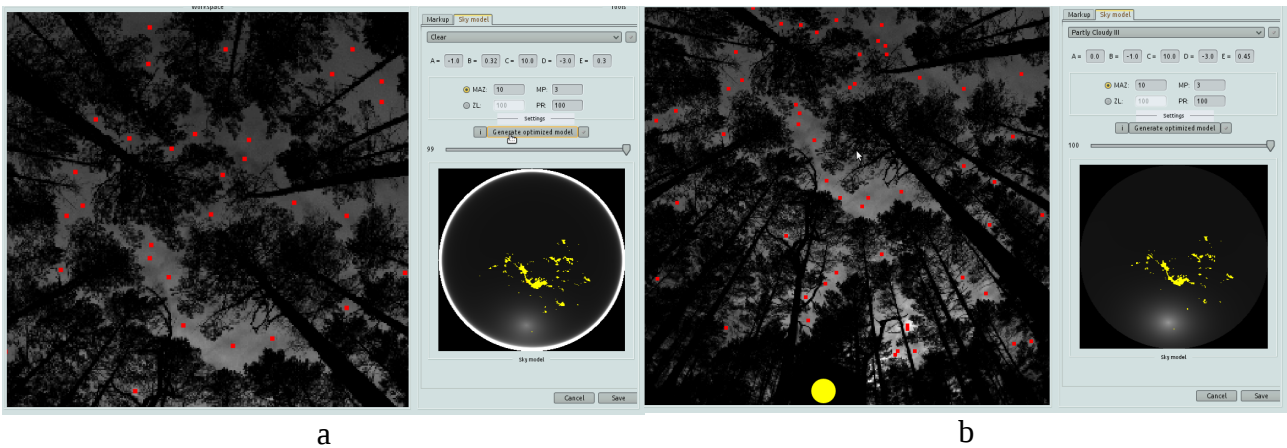



Figure 11. Sky radiance model can be fitted on each image. a) wrong initial solution or lack of samples causes fitted model to predict increase of sky brightness toward horizon for overcast sky. b) Realistic model for overcast sky with slight brightening towards sun. The yellow painted areas indicate local variation which is not possible to describe with the model. Small number of yellow painted pixels ( $1.05 \leq T \leq 1.15$ ), however, is acceptable. The results for this image can be improved by setting sky model weight below 100 which allows interpolation.





Figure 12. The balance between the mathematical model and interpolation method can be set to find best solution.

The clear sky area polygons  can be used to query for calculated transmittance. Select a clear sky area polygon with *SHIFT+drag* and the Navigator near-to-cursor instant zoom image (Figure 7) is replaced with the distribution histogram of gap fraction values (Figure 13). The histogram is not updated automatically.

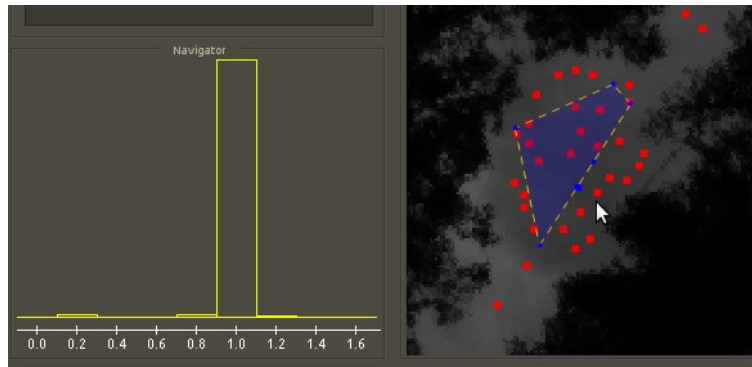


Figure 13. Select (*SHIFT+drag*) a clear sky area polygon to display distribution histogram of calculated transmittance's. The mode value of the histogram must be close to 1.0.

Finally, after image markup and above sky image restoration, click <Save> (Figure 12) to store settings for the image and to return to the list of below canopy hemispherical images. If all the images are processed then send the images further to *Export* section (Figure 4).

## Calculation of canopy gap fraction and export of the results

HSP is designed to calculate canopy gap fraction from hemispherical images. The canopy gap fraction data can be further used in various software programs (GLA, CIMES, CAN-EYE) which are designed for estimation of canopy structural variables (PAI, LAI, clumping) and quantities of absorbed or transmitted radiation. The list of HSP export formats is given in Table (1). Select appropriate number of zenith annuli (sectors) and include sky area masks and exclusion masks in export if needed.

Table 1. HSP export formats

Output	Description
<i>raw statistics</i>	An ASCII text file for each image containing canopy gap fraction for each zenith annulus.
<i>averaged raw statistics</i>	One ASCII text file containing canopy gap fraction for each zenith annulus averaged over all images.
<i>BMP</i>	Canopy gap fraction image is scaled to range 0-255. The canopy gap fraction values $T > 1.0$ are assigned value 255.
<i>averaged BMP</i>	The average gap fraction over all images scaled to range 0-255. The canopy gap fraction values $T > 1.0$ are assigned value 255.
<i>binarized BMP</i>	Each canopy gap fraction image is binarized: 0=plant and 1=sky. A threshold is searched for each zenith annulus according to rule that the average gap fraction in the annulus in the real image must be equal to the gap fraction of the annulus in the binarized image.
<i>averaged binary BMP</i>	The averaged canopy gap fraction over all images is calculated first, otherwise the same as <i>binarized BMP</i> .
<i>Can-Eye package</i>	Canopy gap fraction data suitable for import into CAN-EYE (Weiss, 2013). Gap fraction is given as percentage (0..100) with values $T > 1.0$ scaled to $T = 1$ , the pixels under exclusion masks are assigned value 255.
<i>Transparency PGM</i>	Canopy gap fraction data of each image scaled with 10000 and is stored into standard PGM file.

During the export of results, HSP restores each above canopy sky image in full resolution. Thus, the procedure is slower than the calculations made during the image markup phase. All the created files are stored into the *results* folder under project directory.

## Some practical recommendations

### Before fieldwork

Switch off all image processing related automatics of the hemispherical cameras used for measurements. If possible, calibrate cameras in radiometry lab. Set camera clock to UTC time or according to your time zone (accounting for daylight saving i.e. summer and wintertime is not recommended). Create an image library of different sky conditions to understand the sky radiance distribution over hemisphere. Take test images below forest canopy and carry out image processing in HSP. If possible, compare the results to plant canopy analyzer measurements.

### Fieldwork

It is almost impossible to correct the measurement errors due to taking the images during wrong illumination i.e. direct sunlight. Only the diffuse illumination during overcast (including local cloud that shades the canopy from Sun), before sunrise or after sunset is suitable for canopy gap fraction and canopy cover measurements.

Operate camera in the manual mode (M). Aperture (A) and shutter (S) priority modes can produce overexposure due to the feedback from automatic light measurements by camera. Select appropriate ISO, shutter speed and aperture to avoid any overexposure. Feedback about the settings can be obtained from brightness histogram. Keep the pixel maximum values in the 20-70% range of the sensor maximum value.

Usually, the field sampling schema is determined before field measurements. Some examples of field sampling setup can be found from Garrigues *et al.*, (2002). The number of images needed for representative average can be calculated according to Nilson *et al.* (2011).

The most valuable information is in the notes made during fieldwork about camera settings, field conditions, canopy conditions, sky conditions, etc. Use the autoincremented image number to connect notes and images. Do not zero the image counter in the field camera. Orient camera in respect to North if the aim is to study forest understorey light climate or similar topics.

### Image processing

Experiment with *dcrw* to find the correct list of switches! Experiment with the interpolation and with the CIE model fitting options to find optimal solution. During image markup, distribute the sky sampling markers uniformly over image. Interpolation procedure is preferred method for above canopy sky image restoration, however, do not use too wide search distance, but include mathematical model. Follow the determination coefficient of the model fitting to select balance between interpolation and mathematical model. Decrease model weight if determination coefficient of model fitting is low.

The storage space required for image files can be significant. A project in HSP for 12 below canopy images can easily consume 250MB of disk space to store all image files and results. Create backup copies of the HSP root folder. The approximate time for a experienced user needed for markup and process one single image is about five minutes or more depending on computer CPU speed.

## Acknowledgements

Support for the HSP Project Manager software development was provided by Environmental Conservation and Environmental Technology R&D programme project „Aeglaselt kulgevate nähtuste tuvastamise kaugseiremeetodite täiustamine“ (3.2.0801.11-0012) and Estonian Science Foundation grant no ETF8290.

## References

- Cescatti, A., 2007. Indirect estimates of canopy gap fraction based on the linear conversion of hemispherical photographs: methodology and comparison with standard thresholding techniques. *Agricultural and Forest Meteorology* 143, 1–12.
- Chianucci, F., Cutini, A. 2012. Digital hemispherical photography for estimating forest canopy properties: current controversies and opportunities. *Journal of Biogeosciences and Forestry* 5, 290-295.
- CIE, 2004. ISO 15469:2004/CIE S 011:2003. Joint ISO/CIE standard: spatial distribution of daylight – CIE standard general sky.
- Coffin, D., 2013. Decoding raw digital photos in Linux. [<http://www.cybercom.net/~dcoffin/dcraw/>].
- Flower-Ellis, J.G.K., Olsson, L. 1993. Estimation of volume, total and projected area of Scots pine needles from their regression on length. *Studia Forestalia Suecica* 190, 1-19.
- Frazer, G.W., Canham, C.D., and Lertzman, K.P. 1999. Gap Light Analyzer (GLA), Version 2.0: Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs, users manual and program documentation. Copyright © 1999: Simon Fraser University, Burnaby, British Columbia, and the Institute of Ecosystem Studies, Millbrook, New York.
- Garrigues, S., Allard, D., Weiss, M., Baret, F. 2002. Comparing VALERI sampling schemes to better represent high spatial resolution satellite pixel from ground measurements: How to characterize an ESU. [[http://w3.avignon.inra.fr/valeri/fic\\_htm/methodology/main.php](http://w3.avignon.inra.fr/valeri/fic_htm/methodology/main.php)].
- Hale, S. E., Edwards, C. 2002. Comparison of film and digital hemispherical photography across a wide range of canopy densities. *Agricultural and Forest Meteorology*, 112,(1), 51-56.
- Inoue, A., Yamamoto, K., Mizoue, N., Kawahara, Y. 2004. Effects of image quality, size and camera type on forest light environment estimates using digital hemispherical photography. *Agricultural and Forest Meteorology*,126 (1–2)89-97.
- Javadoc, 2012. <http://docs.oracle.com/javase/6/docs/api/java/lang/Math.html>. (10.12.2012).
- Jonckheere, I., Fleck, S., Nackaerts, K., Muys, B., Coppin, P., Weiss, M. and Baret, F. 2004. Reviews of methods for in situ leaf area index determination. Part I. Theories, sensors, and hemispherical photography. *Agricultural and Forest Meteorology*, 121, 19-35.
- Jonckheere, I., Nackaerts, K., Muys, B., Coppin, P., 2005. Assessment of automatic gap fraction estimation of forests from digital hemispherical photography. *Agricultural and Forest Meteorology* 132, 96–114.
- Kittler, R., 1994. Some qualities of scattering functions defining sky radiance distributions. *Solar Energy* 53 (6), 511–516.
- Kodar, A., Kutsar, R., Lang, M., Lökk, T., Nilson, T., 2008. Leaf area indices of forest canopies from optical measurements. *Baltic Forestry* 14 (2), 185–194.
- Lang, M., Kuusk, A., Möttus, M., Rautiainen, M., and Nilson, T. 2010. Canopy gap fraction estimation from digital hemispherical images using sky radiance models and a linear conversion method. *Agricultural and Forest Meteorology*, 150(1), 20-29.
- Leblanc, S. G., Chen, J. M., Fernandes, R., Deering, D. W., Conley, A. 2005. Methodology comparison for canopy structure parameters extraction from digital hemispherical photography in boreal forests. *Agricultural and Forest Meteorology*, 129(3–4),187-207.
- Macfarlane, C., Michael Coote, M., White, D. A., Adams, M.A. 2000. Photographic exposure affects indirect estimation of leaf area in plantations of *Eucalyptus globulus* Labill. *Agricultural and Forest Meteorology*, 100(2–3), 155-168.

- Nilson, T., Kuusk, A., Lang, M., Pisek, J., and Kodar, A. 2011. Simulation of statistical characteristics of gap distribution in forest stands. *Agricultural and Forest Meteorology*, 151(7), 895-905.
- Rich, P. M. 1990. Characterizing pland canopies with hemispherical photographs. *Remote Sensing Reviews* 5, 13-29.
- Sellin, A. 2001. Morphological and stomatal responses of Norway spruce foliage to irradiance within a canopy depending on shoot age. *Environmental and Experimental Botany* 45,(2), 115-131.
- Walter, J.-M. 2009. CIMES-FISHEYE – hemispherical photography of forest canopies. [<http://jmnw.free.fr/>]. Université de Strasbourg – Faculté des Sciences de la Vie – Institut de Botanique – 28 Rue Goethe, 67083 Strasbourg Cedex France.
- Watson, D. J. 1947. Comparative physiological studies in the growth of field crops. I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. *Annals of Botany* 11,41–76.
- Weiss, M. 2013. Welcome to the CAN-EYE web site. [<https://www4.paca.inra.fr/can-eye>].
- Welles, J.M., Norman, J.M. 1991. Instrument for indirect measurement of canopy architecture. *Agronomy Journal* 83, 818–825.
- Zhang, Y., Chen, J.M., Miller, J.R. 2005. Determining digital hemispherical photograph exposure for leaf area index estimation. *Agricultural and Forest Meteorology* 133, 166–181.