

# PROFILE BASED SUB-PIXEL-CLASSIFICATION OF HEMISPHERICAL IMAGES FOR SOLAR RADIATION ANALYSIS IN FOREST ECOSYSTEMS

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## ABSTRACT:

The analysis of classified hemispherical images of forest stands is a common method in forestry to determine site-related factors for plants. A segmentation of hemispheric images, followed by an intersection with the daily and annual path of the sun, provides a quantitative measure on the solar radiation conditions for young plants. For that purpose reliably classified images have to be generated. The paper describes a method for the sub-pixel classification of hemispherical canopy images. The goal was to develop an automatic method which allows classifying canopy images independent of the type and density of the forest stand and the sky cover. The procedure can be divided into two steps. First the pixels that purely represent the classes sky or vegetation are determined. This is done by analysing radial grey value profiles corresponding to the homogeneity of neighbouring pixels. Inhomogeneous regions usually define border pixels between the two classes. In addition to this texture criterion the multi-spectral information is considered insofar as a pixel can be identified unambiguously as a pure vegetation pixel by its RGB-values. In a second step the remaining unclassified mixed pixels are assigned to these two classes. For that purpose the percentage ratio of each class is determined for each mixed pixel.

## 1. INTRODUCTION

Hemispherical photography using 180° fisheye lenses has been an established method for the measurement of solar radiation in forest ecosystems for many years. It has been used since the late 50s (Evans/Coombe, 1959) to evaluate the radiation conditions in forest stands for the determination of site related factors for young plants.

The basic idea of the technique is taking a hemispheric crown image in a forest ecosystem, segmenting the image in order to identify radiation-relevant open sky areas, and then merging the open sky area with a sun-path model in order to compute the total annual or seasonal radiation for a plant. In contrast to conventional PAR sensors (photosynthetically active radiation), hemispherical images offer the advantage of providing radiation information on the whole hemisphere from a single image. PAR sensors do not deliver spatially resolved information and therefore require the measurement of long time series. The digital hemispherical RGB-images have to be segmented and sub-pixel-classified in order to obtain precise geometrical information about radiation relevant areas (sky) and non radiation relevant areas (vegetation) (see figure 1). The classified hemispherical images can then be combined with radiation and sun path models in order to determine specific radiation values that are used for silvicultural analysis.

Until now the method has usually been based on analogue photography (Dohrenbusch, 1989; Wagner, 1998) which is disadvantageous from an automation point of view and also concerning the reproducibility of results. In the recent years

digital cameras with a resolution and image format that allow for a change-over to high-resolution digital hemispherical images, have become available. The images used in this paper were taken with a 4500 x 3000 pixel camera equipped with a 180° fisheye lens.

To prepare the images for the radiation analysis two tasks have to be solved: The first task is the geometric modelling and calibration of the fisheye lens camera system in order to obtain the geometric relation between image space and object space (Schwalbe, 2005). The second and main task, which is presented in this paper, is the segmentation and classification of hemispherical canopy images.

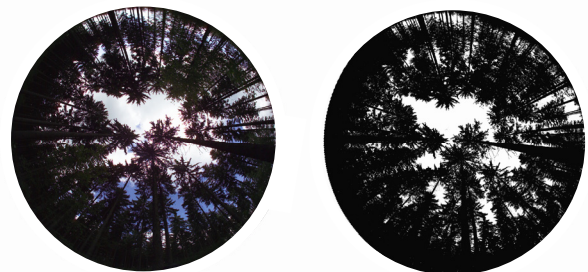


Figure 1. Original and classified hemispheric image

So far, established methods in this field have been based on scanned black-and-white analogue imagery, which were segmented in a thresholding using one optimized threshold to

divide the image into the two classes, sky and vegetation (Ishida, 2004).

Using a global threshold has the disadvantage that satisfactory results are only produced when the weather conditions match certain criteria. In most cases a homogenous clouded sky is required. This considerably reduces the days of a year that are appropriate for taking images. Therefore the goal of the work presented here was to develop a method which allows for a fully automatic sub-pixel classification and which is adapted to be used at different weather conditions, different types of forest stands and to the special features of hemispherical images.

## 2. SPECIAL CHARACTERISTICS OF HEMISPHERICAL IMAGES

Hemispherical images have special characteristics concerning the constancy of the intensity, weather depending variations and a dominance of the blue channel. Even within one image, a consistent spectral signature for the class sky can not be defined. Reasons for this are intensity differences between the centre of the image and the border as well as intensity differences in azimuthal direction, depending on the position of the sun. Furthermore the spectral signature depends on the weather condition. In this respect a partly cloudy sky depicts an extreme situation. Due to the fact that each image has to be taken as a back lighted shot, the sky areas are usually overexposed whereas the vegetation areas are underexposed. If the exposure time is too long small branches are outshined (see figure 2a). Otherwise if the exposure time is too short information about small translucent gaps in the canopy are getting lost (see figure 2b).

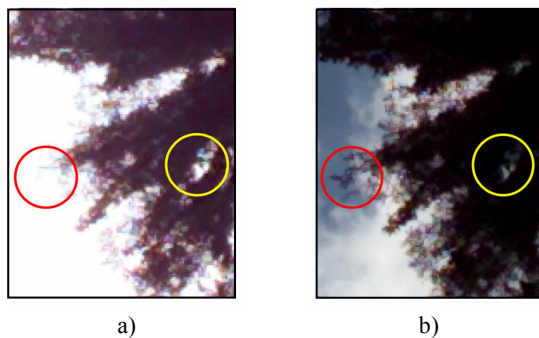


Figure 2. Different loss of information for different exposure times

The best solution for the problem would be to use a camera with a high dynamic range. The dynamic range of a camera with a 12 bit sensor is not sufficient, and cameras with a higher dynamic range, which can be equipped with a 180° fisheye lens and are manageable in the field, are hardly available on the market. Another solution of the problem might be the use of two images taken at the same position but with different exposure times. The disadvantage is that because of the time lag between the two records wind may cause structural changes of the canopy and single branches may be located at different positions in the two images. Therefore the optimal exposure time of a hemispherical image which means the minimization of the loss of information is a difficult task. Proposals for the determination of the optimal exposure of canopy images are given in Zhang et al., 2005.

The characteristics of hemispherical images shown above restrict the applicability of standard multi-spectral classification techniques. Jonckheere et al., 2005 compared and tested a high number of common classification techniques in order to find out

which method is most suitable for the classification of hemispherical images. Most of the classification results obtained by using commercial image processing software are not satisfying. Hence a method has to be developed that is adapted to the special requirements of the sub-pixel classification of hemispherical canopy images.

## 3. CLASSIFICATION METHOD

### 3.1 Overview

In some cases it is not possible to distinguish between sky areas next to the border of the image and vegetation areas in the middle of the image in a global procedure, because their colour and intensity values can be very similar. Using commercial image processing software most misclassifications are caused by this fact. Therefore it is not reasonable to develop a global classification technique but a method that assesses pixels locally referring to their neighbourhood.

Due to the overexposure of sky areas and the underexposure of vegetation areas the grey values within these regions are similar whereas the transition areas between both classes are rather inhomogeneous. This means that the texture is a good criterion to differentiate between pure pixels and mixed pixels. Since each image is a back lighted shot and the RGB-channels are highly correlated, the multi-spectral information can only be used in a limited way.

Because of these facts the basic principle of the developed method is to determine first the pixels that unambiguously represent the classes sky and vegetation mainly by using the texture criterion but also the multi-spectral information if possible.

Second, the remaining unclassified mixed pixels are assigned to the two classes by determining the percentage of each class contained in a mixed pixel, taking into account the local neighbourhood of the pixel. As a result a grey value image is obtained wherein a grey value of 255 represents pure sky pixels and a grey value of 0 represents pure vegetation pixels. The remaining mixed pixels are grey value coded corresponding to their percentage of the class sky. Such an image can be used as input to the solar radiation calculation algorithm. This algorithm combines the geometrical information about sky and vegetation sectors of the hemisphere given by the classified hemispherical image with sun path models and radiation models, in order to derive radiation values for the position where the image was taken for an arbitrary time.

Based on this principle the classification method consists of four steps:

1. Detection of homogeneous regions to separate pure pixels from mixed pixels.
2. Histogram analysis to derive rough global thresholds that are applied to the homogeneous regions in order to obtain initial regions of pure pixels of both classes (sky and vegetation).
3. Classification of homogeneous regions based on the preliminarily found initial regions of pure pixels of sky and vegetation areas, by locally assigning unclassified pixels to one of the classes.
4. Sub-pixel classification of the inhomogeneous regions by analysing the pure-pixel neighbourhood of each mixed pixel.

Each work step will be explained in more detail in the following.

### 3.2 Detection of homogeneous regions

The characteristics of hemispherical images require local methods rather than global methods. Therefore it is important to define regions of interest all over the image and as extensive as possible. Furthermore the procedure of defining those regions that contain pure vegetation and sky pixel is desired to work without human interaction. For that purposes, the fact that the image is a back lighted shot is utilised. On the one hand this fact is disadvantageous concerning the use of colour information but on the other hand it is advantageous concerning the use of texture information. Sky areas are characterised by the local homogeneity of their pixels. In the hemispherical back lighted images the vegetation areas are homogeneous too. Neighbouring pure vegetation pixels are usually concentrated within small grey value ranges. Due to the dynamic range of common digital cameras the grey value variation within those ranges is low even if the exposure of the image is optimal. Figure 3 shows a typical histogram of a well exposed canopy image.

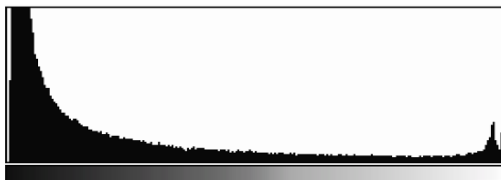


Figure 3. Typical histogram of a canopy image taken with optimal exposure

This means that homogeneous regions can be declared as regions of pure pixels independent on their class. Inhomogeneous regions can be seen as transition areas between both classes which mean that they consist of mixed pixels. Thus an unmixing of those pixels has to be performed (see chapter 3.5).

The first task is to determine homogeneous regions of the images. For that purpose a profile analysis is performed so that profiles of the image are defined. Then by analysing the grey values of neighbouring pixels along each profile a decision is made whether these pixels belong to homogeneous or inhomogeneous regions. The profiles should be defined radially, starting in the principle point of the hemispheric image. On the one hand such profiles follow the direction of the tree trunks, and on the other hand they are crossing most of the branches orthogonally which allows a better detection of different homogeneous regions.

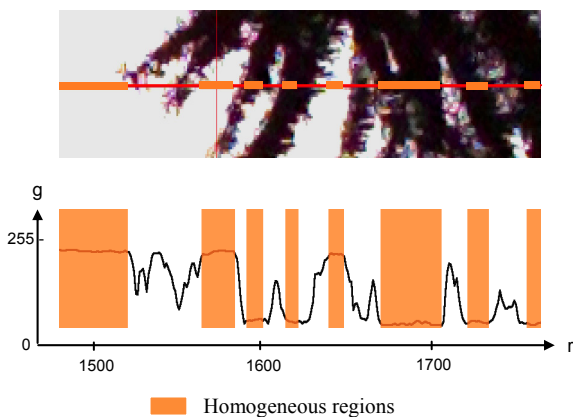


Figure 4. Profile analysis

Figure 4 shows a section of a radial profile of a hemispherical image and the according intensity diagram. It can be seen that flat parts of the graph correspond to pure sky or vegetation areas in the image. To extract those flat parts, each pixel of the profile is compared to six neighbouring pixels on its radial profile. If the grey value differences do not exceed a certain limit, the central pixel and its neighbour pixels are defined as a homogeneous region. In figure 4 these pixels are marked with orange colour.

Before analysing a pixel on the texture criteria, its RGB-values are considered. A number of conditions are integrated in the algorithm which test to which extends the colour information of the pixel can be used for its identification as sky or vegetation pixel. An identification of a pixel as vegetation pixel e.g. is given by the fact that the grey values of the green and red channel are significantly higher than the grey value of the blue channel. In such cases the pixel is classified as vegetation independent on the texture criteria. The result after processing all profiles is shown in figure 5.

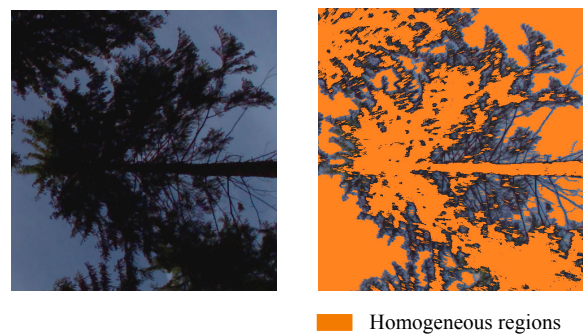


Figure 5. Original image (left) and detected homogeneous regions (right)

As shown in figure 5, a large number of pure pixels are detected by the procedure as described above, but it is still not apparent which class they belong to. Hence, in the following two steps (chapter 3.3 and 3.4) the homogeneous regions are classified.

### 3.3 Histogram analysis

It is not recommendable to use a single global threshold to separate the two classes because sky and vegetation areas may have similar intensity values depending on their location in the image. Due to the local differences an overlap of sky- and vegetation intensity value ranges exists which prevents a reasonable separation. This is particularly difficult for weather conditions such as blue sky with scattered cumulus clouds (see figure 6).



Figure 6. Difficult weather condition

Therefore in a first step a rough upper and lower global threshold is searched for. The range between these thresholds is the grey value range of the histogram where the intensity values of the two classes are overlapping. To avoid misclassifications, only those pixels are classified at this stage, which consist of

grey values lower than the lower threshold or higher than the upper threshold. In this way initial regions are classified. In a second step the unclassified regions are assigned to the two classes based on local analysis using the initial regions (see chapter 3.4). The search for the preliminary upper and lower threshold is performed as a histogram analysis of the detected homogeneous regions. The definition of the thresholds should be automated, and the parameters should be universally applicable to different types of hemispherical images (different weather conditions, different densities and types of forest stands). Since the thresholds are merely used to provide a sufficient basis for the ensuing local classification procedure, they can be set quite roughly. This means that simple rules can be applied to set the thresholds.

To generate the thresholds, the histogram of the homogeneous regions is first smoothed by iteratively applying a moving average filter. The filter removes high-frequent variations in the histogram and allows for a more reliable analysis.

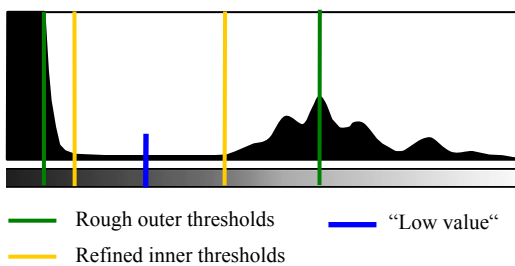


Figure 7. Histogram analysis of homogeneous regions

These are the two outer thresholds shown in figure 7 in green colour. The local classification is a relatively time-consuming process. To reduce the amount of pixels that have to be locally analysed (and thus the computation time), these thresholds are refined by searching for the lowest value between these “outer thresholds”. Then average values are calculated from the histogram values lying between this low value and the upper or lower threshold respectively. Starting at the “low value” it is searched for the first values that exceed the accordant calculated average values. These values pass for the refined inner thresholds (see figure 7) that are finally used to define the initial classified homogeneous regions. All pixels with grey values higher than the upper threshold are classified as sky whereas pixels with grey values less than the lower threshold are classified as vegetation (see figure 8). Pixels with intensity values that lie between the thresholds can not be assigned unambiguously to one of the classes and are therefore locally analysed in the next step.

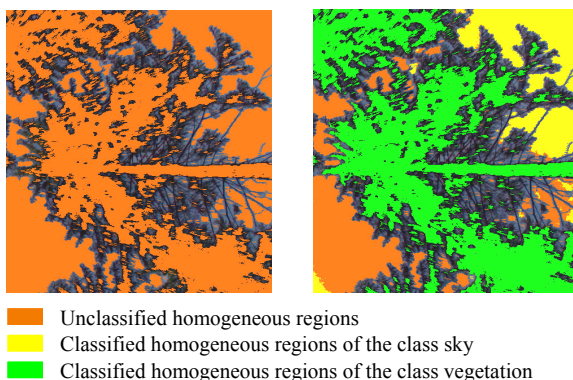


Figure 8. Detected homogeneous regions (left) and initial classified regions detected using global thresholds

### 3.4 Classification of homogeneous regions

In the following the assignment of the pixels of the remaining homogeneous regions to their appropriate class takes place by comparing their grey values to the grey values of neighbouring pixels which were already classified by thresholding as explained in the previous chapter. For this purpose the neighbourhood of an unclassified pixel is spirally scanned until a sufficient number of pixels (e.g. 30 pixels) that belong to the class sky as well as of pixels that belong to the class vegetation are found (see figure 9).

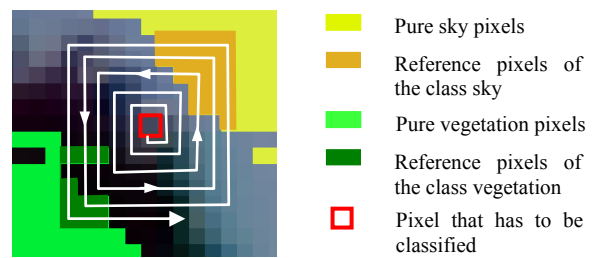


Figure 9. Search for reference values

The intensity value of the unclassified pixel is now compared to the average intensity values (reference values) of those neighbour pixels, which have already been classified. The unclassified pixel is then assigned to the class to which its intensity value is nearest. As a preliminary result all pixels of homogeneous regions are classified (see figure 10).

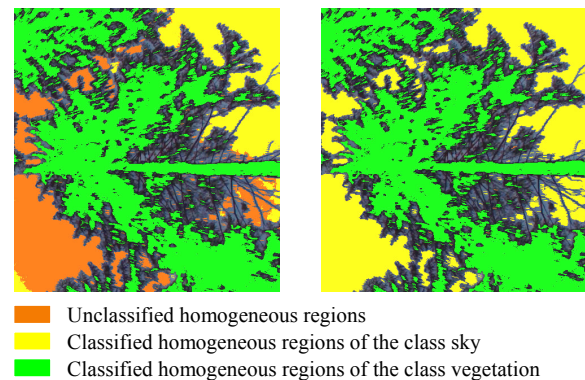


Figure 10. Initial classified regions (left) and completely classified homogeneous regions (right)

This local assignment method, which will be used again for the classification of inhomogeneous regions (see chapter 3.5), is rather time-consuming because of the search for reference values for each pixel, that has to be classified. With regard to the high resolution of the images and the goal to accomplish a method that is practicable, it is necessary to consider the computing time. Therefore the assumption is made that the reference values are very similar for unclassified pixels that are closely situated together. Thus, reference values have not to be found for every single pixel but only for pixels in a certain raster (e.g. for each tenth pixel in x- and y-direction). All other unclassified pixels that are no raster points are evaluated on the basis of the reference values for the nearest raster pixel. This decreases the computing time considerably. A disadvantage, however, is the fact that errors in the reference values propagate to the neighbouring pixels.

### 3.5 Sub-pixel classification of inhomogeneous regions

In the last step the remaining mixed pixels have to be analysed. To realise a sub-pixel classification for these pixels the percentages of the two classes have to be determined for each mixed pixel. For that purpose the intensity value of a mixed pixel is compared to the intensity values of neighbour pixels that are pure pixels. Hence, the nearest reference pixels for mixed pixels are searched for, using the same principle as it is already described in chapter 3.4 (see figure 9). There, the average intensity value of the reference pixels of the class sky corresponds to a percentage of 100% of the class sky and the average intensity value of the reference pixels of the class vegetation accordingly corresponds to a percentage of 0% of the class sky. The percentage for a mixed pixel is now obtained by linear interpolation between the two reference values. If the intensity of a mixed pixel is higher than or equal to its reference value of the class sky, it is evaluated with a percentage of 100%. If it is lower than or equal to its reference value of the class vegetation, it is evaluated with a percentage of 0%. This means that pure pixels which were not detected as pure pixels after the profile analysis can now still be classified as pure pixels. Then the percentage values are transformed into grey values.

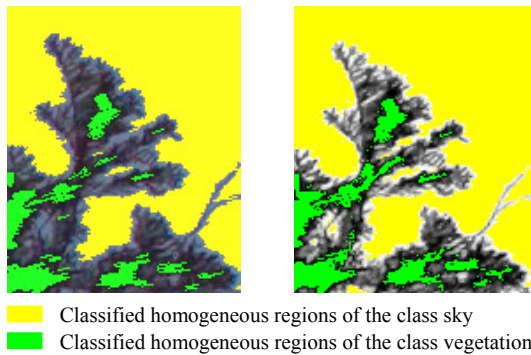


Figure 11. Classified homogeneous regions (left) Classified grey value coded mixed pixels (right)

Figure 11 shows the mixed pixels replaced by the grey values that correspond to the percentage of the class sky in the pixel. The final step is to allot the grey values of 0 or 255 respectively to the pixels of the homogeneous regions according to the class they belong to. The final result is shown in figure 12. The classified images can now be used as input for the radiation calculation analysis.

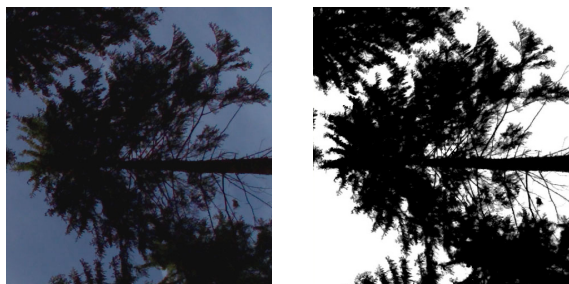


Figure 12. Original image (left) and classified image (right)

## 4. RESULTS

The verification of the classification results is difficult because there are no countable objects that can be compared to reference objects. Based on the classified image itself, only a subjective assessment can be made by visual comparison between single regions of the original image and the classified image. This was done to analyse the influence of the following factors:

1. Different weather conditions
2. Different densities of forest stands
3. Different exposure settings

### 4.1 Different weather conditions

Hemispherical images of forest stands are best taken when the sky is homogeneously clouded. For this weather condition the best classification results could be obtained using conventional methods. One goal of the presented work was to realise a sufficient classification of images taken at different weather condition. Because of the local search for reference values it is possible to successfully classify images showing inhomogeneous clouds, scattered clouds or even unclouded sky. The latter is possible e.g. in the early morning hours when there is still twilight. It has to be considered that the sun should not appear in the images. This would lead to strong irradiations and a loss of information in the image.

Though it is possible to analyse images of different weather conditions, the weather conditions influence the reliability of the classification. Images taken at homogeneously clouded sky can still be classified most reliable. Problems arise when the sky is scattered clouded. Then fragment-like misclassifications can appear at the borders of the clouds. The reason is that pixels located at cloud borders are detected as inhomogeneous pixels. These pixels are then treated as mixed pixels and classified as explained in chapter 3.5. Due to the different intensities between the blue sky and the brighter clouds, wrong reference values are found in some cases. This means that the accordant mixed pixel is not classified as sky but obtains a slightly lower grey value (see figure 13).



Figure 13. Original image with clouds (left) and classified image with fragments caused by cloud borders (right)

### 4.2 Different densities of forest stands

In case of very dense forest stands the problem might occur that, especially next to the borders of the image, no homogeneous regions of the class sky are available. That means reference pixels of the class sky can not be found in the neighbourhood of a mixed pixel of this region but in a higher distance to it. Thus, two problems arise: First, the wide-ranging search for reference pixels increases the computing time and second, reference pixels that are found in a high distance to its accordant mixed pixel might be in some cases irrelevant for the mixed pixel.

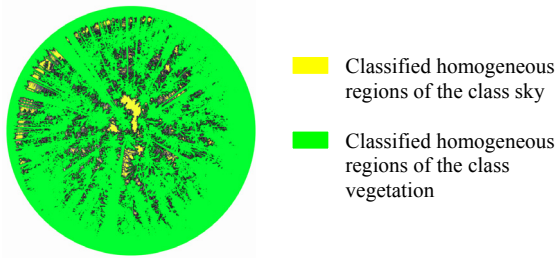


Figure 14. Classified homogeneous regions of a hemispherical image of a dense forest stand

This means that for mixed pixels next to the image border reference values for the class sky can only be found in the middle of the image (see figure 14). Those reference pixels are then usually too bright, so that for the mixed pixel a grey value is calculated which is too low.

#### 4.3 Different exposure times

The correct exposure of the images is a problem that cannot fully be solved by the classification method itself. As already mentioned, the hemispherical images are always back lighted shots. This causes the problem that the images are often partly under- or overexposed. If an overexposed image has to be classified, the method has to deal with a lack of information in the bright parts of the image. Small branches are outshined and can therefore not be detected. The same applies for underexposed images: Small holes in the canopy are getting lost. So it is an important task to optimize the exposure of the images.

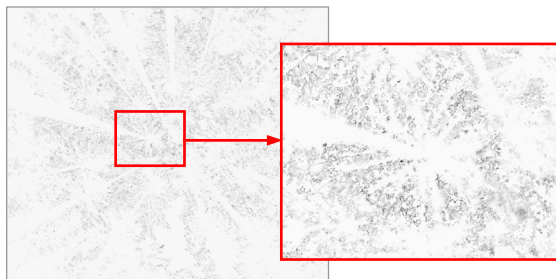


Figure 15. Difference image of classified images taken with different exposure times

Figure 15 shows the grey-coded difference between classification results of differently exposed images taken at the same position. As one can see, the mixed pixels are differently unmixed due to the different intensity values of the homogeneous regions. This can be explained by the effect of clipping information from the linear percentage interpolation process when regions of the image are over- or underexposed.

## 5. CONCLUSION

A method has been developed that allows for a fully automatic classification of hemispherical forest canopy images in solar radiation measurement tasks. The method shows the advantage of applicability over a wide range of weather conditions. This could be achieved by replacing global thresholding techniques in the image segmentation and classification by texture based local analysis procedures. The special characteristics of hemispherical images have been considered.

## 6. FUTURE PROSPECTS

Future work on the classification method will address the definition of additional conditions to avoid problems which may occur at cloud borders or in images of very dense forest stands. Furthermore, the quality of the methods will be validated in a series of practical tests. These tests will comprise a direct comparison of the results of single shot hemispheric image processing with results obtained from time series of PAR sensor observations. The validation will be performed for different types of forest stands and different weather conditions. This validation will not only deliver a quality measure for the classification process, but for the whole procedure. In addition, a detailed quantitative analysis of the influence of the factors explained in chapter 4 will be performed.

## 7. ACKNOWLEDGMENTS

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- Colour versions of the images of the paper are available at: <http://www.tu-dresden.de/ipf/photo/publikationen/2006.htm>