Sky view factor measurement by using a spherical camera

Tsuyoshi Honjo*†, Tzu-Ping Lin† and Yuhwan Seo†

*Graduate School of Horticulture, 648, Matsudo, Matsudo-shi, Chiba, Japan
†Department of Architecture, National Cheng Kung University, Tainan, Taiwan

Abstract

Sky view factor (SVF) is a ratio of sky in upper hemisphere and is an important index for many environmental studies. Frequently used method for measuring SVF is taking fisheye image of upper hemisphere by a camera with fisheye lens (Nikon FC-E8 and FC-E9). In this study, we devised the usage of a spherical camera (RICOH Theta S), which can take a picture with 360° field of view (FOV), for SVF measurement. Applicability of the spherical camera to the measurement of SVF is tested by comparing with conventional fisheye cameras. The result showed that it can take the same quality of fisheye images as conventional fisheye camera and can be applied to the measurement of SVF. Accuracy and causes of errors are considered and as a conclusion, the spherical camera has enough performance for the replacement of conventional cameras. The algorithm of making fisheye images of different projection methods and of calculating SVF are written as programs in R.

Key words: Binarization, Equal-area projection, Equidistant projection, Fisheye converter, Panorama image

1. Introduction

Sky view factor (SVF) is a ratio of sky in upper hemisphere. It is a measure of the degree to which the sky is obscured by the surroundings for a given point and a common parameter used to characterize the geometry of urban canyons (Grimmond et al., 2001). SVF is an important index for many environmental studies. In the area of forestry, it is used for the analysis of light environment in forest canopy (Frazer et al., 2001; Inoue et al., 2004; Jonckheere et al., 2004). In the area of urban climate, it is regarded as one of the most important factors governing urban-rural and intra-urban temperature differences (Svensson, 2004; Unger, 2004; Holmer et al., 2007; Chen et al., 2012). SVF is also an important factor for calculating human thermal comfort (Matzarakis, 2007; Lin et al., 2010, 2012; Chen et al., 2014; He et al., 2015). Recently, SVF can be calculated from digital surface model (Brown et al., 2001; Lindberg, 2005; Lindberg et al., 2008; Gál et al., 2009; Kastendeuch, 2013), but direct measurement of SVF from fisheye image is also important and necessary (Hämmerle et al., 2011).

Most frequently used method for measuring SVF is taking fisheye image of upper hemisphere by camera. Nikon’s fisheye converter, FC-E8 and FC-E9 have been commonly used as an instrument to measure the SVF in many studies (Grimmond et al., 2001; Brown et al., 2001; Frazer et al., 2001; Chapman and Thormes, 2004; Inoue et al., 2004; Holmer et al., 2007; Gál et al., 2009; Unger, 2009; Park and Tuller, 2014; He et al., 2015). But these models have no successors available on the market. Digital SLR cameras with fisheye lens can be used for the measurement of SVF but they are not easily replaced with FC-E8/9 because of the bigger size and the higher cost.

We thought usage of a spherical camera is one of the solution for the lack of instruments of SVF measurement. A spherical camera take a picture with 360° field of view (FOV) like Google Street View. RICOH Theta which consist of two hemispherical lenses is the typical model of this kind. There are several similar products by now such as Nikon KeyMission 360, GoPro Fusion, Samsung Galaxy Gear 360, etc.

In this study, applicability of the spherical camera on the measurement of SVF is presented by comparing with conventional fisheye camera. The main objectives of this study are to (1) examine whether the spherical camera can produce the same quality of fisheye images as conventional fisheye lens camera, (2) test the accuracy of the measurement of SVF by the spherical camera and (3) show the effectiveness of the programs made in this study by comparing with existing software. The programs use the algorithm of making fisheye images of different projection methods and calculating SVF.

2. Method

2.1 Spherical camera and fisheye camera

Cameras used in this study is shown in Fig. 1. As a spherical camera, RICOH Theta S (hereafter, Theta) was used. As a reference of conventional fisheye camera, we used Nikon Coolpix 8800 with fisheye FC-E9 converter lens and Nikon UR-E18 converter adapter (hereafter, FC-E9) and Nikon Coolpix 4500 with fisheye FC-E8 converter lens (hereafter, FC-E8), which are also shown in Fig. 1. The resolutions of fisheye images of FC-E9 and FC-E8 are 1870 × 1870 and 1640 × 1640 respectively.

In the measurement of SVF with FC-E8/9, the camera should face exact zenith direction and a bubble level is used to measure the flat surface and to adjust the camera direction. The camera should be fixed on the tripod and the bottom face of the camera was set to be horizontal as much as possible by using the bubble level.

The zenith position of the images taken by Theta can be
automatically corrected with a software, Spherical Viewer (RICOH), because pitch and roll angles are recorded with the image taken. The corrected image is output as the same size of the cylindrical projection image where the zenith is top. The tripod and the procedure of adjustment with a level is not necessary. The picture is taken only by pushing the shutter on Theta or by using the application of the smart phone. To avoid the user is taken in the picture of upper hemisphere, it is better to take the picture over the head. Pitch and roll angle of the Theta at which the images were taken are recorded as Exif format in its images.

In this study, test images were taken in the Matsudo campus, Chiba University, Japan by the cameras at the same points and used for the analysis.

2.2 From Theta image to fisheye image

The overview of the procedures for the SVF calculation is shown in Fig. 2. Images of Theta are recorded as cylindrical equidistant projection. We transformed the images cylindrical images to fisheye images "transformation 1" in Fig. 2.

In Fig. 3, diagram of transformation from a cylindrical image Fig. 3a to fisheye images of equidistant projection Fig. 3b and equal-area projection Fig. 3c are shown. The resolutions of cylindrical image Fig. 3a and fisheye images Figs. 3b and 3c of Theta are 5376 × 2688 and 2688 × 2688 respectively. If we carefully compare these fisheye images, the center area of the equal-area projection is broader than equidistant projection. Equidistant projection image is used for input format of some softwares for SVF calculation because many of fisheye lens uses this projection method. But equal-area (equisolid angle) projection image is used for the calculation of SVF, because SVF is defined as the ratio of the sky in the equal-area projection image in this study.

Simple procedures of resampling are done to make the images of Figs. 3b and 3c. For the conversion from the cylindrical projection image of Theta to the fisheye images of equidistant and equal-area projection, we use some equations explained below.

The projection methods are defined as follows.

\[ r = f \cdot \theta \]  
\[ r = 2 \cdot f \cdot \sin \left( \frac{\theta}{2} \right) \]

where \( r \) is distance from the center of the image to the point of interest as a function of the angle \( \theta \), \( f \) is focal length, \( \theta \) is 0 in the horizontal direction and \( \frac{\pi}{2} \) in the zenith direction. The relation between the pixel position, \( y \) and \( \theta \) is shown as,

\[ y = \frac{2 \cdot l \cdot \theta}{\pi} \]

where \( l \) is pixels corresponds to the angle \( \frac{\pi}{2} \). The size of cylindrical projection image of Theta is \( 4 \cdot l \) in horizontal direction and \( 2 \cdot l \) in vertical direction. The size of fisheye images of equidistant and equal-area projection is \( 2 \cdot l \times 2 \cdot l \).

The transformation of the pixel value from the point \( (x, y) \) of the Theta image to the point \( (u, v) \) of the equidistant fisheye image is written as follows.

\[ u = y \cos \left( \frac{\pi}{2} \cdot \frac{x}{l} \right) \]  
\[ v = y \sin \left( \frac{\pi}{2} \cdot \frac{x}{l} \right) \]

The equations (4) and (5) can be rewritten as equations (6) and (7) which are more convenient to make the fisheye image.

\[ x = \frac{2 \cdot l \cdot \tan^{-1} \frac{v}{u}}{\pi} \]  
\[ y = \sqrt{u^2 + v^2} \]

About the transfer of the pixel value from the point \( (x, y') \) of the Theta image to the point \( (u, v) \) of the equal-area fisheye image, same \( x \) as equation (6) is used and \( y' \) is expressed by the

![Fig. 1. Cameras used in this study. Nikon Coolpix 8800 with fisheye FC-E9 converter lens and Nikon UR-E18 converter adapter (left) and Nikon Coolpix 4500 with fisheye FC-E8 converter lens (middle) and Ricoh Theta S (right).](image)

![Fig. 2. Procedures from taking photos with Nikon FC-E8/9 and Theta S to sky view factor measurement. There are some intermediate images (fisheye and binarized fisheye) in the procedures. The details of the R programs of the procedures are shown on the web (https://github.com/honjo7777/theta2svf, eqdist2equisolid).](image)
following equation.
\[
y' = \frac{4 \tan^{-1}\left(\sqrt{\frac{u^2 + v^2}{l}}\right)}{\pi}
\]

(8)

2.3 Binarization, transformation and calculation of SVF

As the preparation for the calculation of SVF from fisheye images, the image processing of binarization is executed to divide the sky area from other area (“binarization” in Fig. 2 and Fig. 4). Both binarized equidistant and equal-area projection images are shown in Fig. 4. In equal-area projection, the area near zenith is relatively enlarged compared to equidistant projection. SVF value means ratio of area in the fisheye image in Fig. 4. From the definition of SVF, the value of Fig. 4b is considered as proper SVF. The program for above calculation of SVF and the procedures of Fig. 2 was written in R.

2.4 Transformation from equidistant to equal-area projection

Equidistant projection is used for the fisheye images taken by both FC-E8 and FC-E9 but equal-area projection image is used for the calculation of SVF. Transformation from equidistant to equal-area projection should be done before the calculation of SVF (“transformation 2” in Fig. 2). The transformation can be done for either the original fisheye photo (from Figs. 3b to 3c) or binarized fisheye image (from Figs. 4a to 4b).

After this process, image of Fig. 4b can be used for the calculation of SVF. The number of the white pixels of Fig. 4 are counted and SVF is obtained by dividing the number of all pixels in fisheye image (“counting” in Fig. 2). SVF of equidistant projection is shown for comparison with that of equal-area projection. In equal-area projection, the area near zenith is enlarged and 2.9% decreased value is shown in equidistant projection in Fig. 4.

The R program of the above transformation is shown at the following URL.
https://github.com/honjo7777/eqdist2eqsolid

2.5 Comparison with Rayman

Rayman is a software for thermal comfort index and also can calculate SVF (Matzarakis et al., 2007). The result of the R program is compared with the result of Rayman. Although the algorithm of Rayman is not open, both should use the same mathematical method in the calculation of SVF. Rayman adopted equidistant projection image as input format. One of the reason
is that most of fisheye cameras use equidistant projection like FC-E8/9. It seems to convert the image to equal-area projection inside the software. Another difference is that Rayman may converts the fisheye images to 480 × 480 pixels in the calculation of SVF while the R program use the original size of the fisheye images.

3. Result and Discussion

3.1 Fisheye images

Fisheye images taken by FC-E8/9 and transformed fisheye image of Theta are shown in Fig. 5. Visual quality of the images of all cameras are almost same but for the small objects, Theta is slightly better because of its higher resolution.

When the images of Fig. 5 are overlaid, the images show generally good agreement. But in the details, there are unmatched areas. One reason of the error caused by simple setting of flat level. Although we carefully set the flat surface with a bubble level, it is difficult to set the camera face to the zenith. In the case of Theta which can record pitch and roll angle, 1 degree of pitch and roll is frequently observed even if we carefully set the surface. For FC-E8/9, same amount of error is assumed but correction is difficult, because there is no information of pitch and roll angles which are recorded. Another reason is the lens characteristics. Although the images are called equidistant, there is some inhomogeneity of the angle/pixel. In the case of FC-E8/9, the angle/pixel near the outer edge of the circle is larger than the center of the circle. Theta has two fisheye lenses which usually faces horizontal direction and two fisheye images are synthesized to make one image. The outer edge of fisheye lenses locates line on the center of the image. On this line, the part of Theta itself in the image is erased and this cause inhomogeneity of the angle/pixel.

In Fig. 6, outer edges of the images are enlarged. It was difficult to define the edge circle of the images in the case of FC-E9 because the image of the edge is obscured. Images taken by other conventional cameras with fisheye lens sometimes have the same problem. FC-E8 has clearer border of images near the edge and Theta has clear outer edge because edge position is defined in the original image.

With the comparison of Fig. 5 and Fig. 6, FOV of Theta and FC-E9 is almost the same. We also measured the FOV of the other images and obtained same results. Because FOV of Theta fisheye is 180°, FOV of FC-E9 is considered to be nearly 180° which is little less than the specification value of 183°.

In the case of FC-E8, although the specification of FC-E8 is 183°, the actual FOV of FC-E8 measured in this study was about 186°. Grimmond et al. (2001) reported that the FOV of FC-E8 was 189°, which is larger observation than ours. Considering that, we used the images of FC-E8 with -6° correction of FOV in measuring SVF.

Fig. 5. Fisheye images taken by Nikon Coolpix 8800 with FC-E9, Nikon Coolpix 4500 with FC-E8 and Ricoh Theta S (equidistant projection).

Fig. 6. Images near the bottom edge of Fig. 5.
3.2 Test images for SVF analysis

Example images to test the SVF value are taken by Theta and FC-E8/9 at the 33 points of Matsudo campus, Chiba University. Images of Theta and FC-E8 at some points are shown in Fig. 7. Images of FC-E9 are almost the same as the images in Fig. 7. These images are binarized and used for the calculation of the SVF.

3.3 Comparison of SVF

SVFs were calculated for the images and the comparison of SVF taken by the cameras is shown in Fig. 8. There were some differences between the cameras but they are practically considered as same. In the case of the images with high ratio of trees as shown in Fig. 7, the difference is larger because ratio of leaves and branches is largely affected by the contrast of the images. This is caused by the difference of aperture and shutter speed of each camera. The result indicates that Theta can be used for SVF measurements instead of FC-E8/9.

3.4 Effect of threshold value

In making binary images, a color image is transformed to gray scale image at first. After that, gray scale image is binarized with threshold value. In the gray scale image, 0 is assigned to black color, 1 is assigned to white color and gray color takes the values between 0 and 1. In binarization, gray scale color more than the threshold value is changed to 1 and otherwise, it is changed to 0. If the threshold value changes, SVF also has different value as shown in Fig. 9. Images with threshold value of 0.5 and 0.9 are seemingly very similar but SVF is different about 6%. In Fig. 10, same picture of Fig. 9 is used and SVF variation according with the threshold value is shown. SVF is considered as a function of the threshold value. If the threshold value increases, the SVF decreases. The difference is bigger than the other cause of the error. Most of the difference of Fig. 10 is considered as the influence of threshold value in making binary images. Especially, if the trees or plants are largely included in the image, it is difficult to find optimum threshold value.

3.5 Comparison of the R program and Rayman

SVFs calculated by the R program and Rayman are compared in Fig. 11. To make the condition same, the input images used for this comparison were 33 binarized equidistant fisheye images taken by FC-E8 (1640 × 1640 pixels). Both SVF values show precise agreement and the R program and Rayman show same performance. With the images of large area of trees, there is some difference (points in the circle in Fig. 11). This effect is happened because in Rayman the resolution is reduced to 480 × 480 pixels. When we use the images with reduced to
4. Discussion

4.1 Applicability of Theta

From the comparison shown in Fig. 7 and 8, fisheye images taken by Theta had the same quality with those of FC-E8/9. On 480 × 480 pixels as input, the difference shown in the circle in Fig. 11 was disappeared.

Fig. 11. Comparison of SVF calculated by Rayman and the R program. Same 33 binarized test images were used.
the emergence of FC-E8, the applicability for the measurements of SVF and forest canopy structure were shown in early researches (Englund et al., 2000; Frazer et al., 2001; Grimmond et al., 2001). Considering the results in this study shown above, Theta will be used as the standard instrument for the SVF measurement like FC-E8. Not only Theta, but other spherical cameras are also worth testing for the SVF measurements.

Theta has some advantages compare to FC-E8/9 or other conventional Digital SLR cameras with fisheye lens. The size and weight are smaller than that of FC-E8/9 (size: 44 mm × 130 mm × 22.9 mm, weight:125 g). In the field, the small size and weight have many advantages and sometimes critical for beginning the measurement. Continuous measurement is easy by using the time lapse function or by taking a movie and capturing the images.

The function of the auto-correlation of the horizontal level of the images is another advantage. By this function, a tripod and adjusting by a level is not necessary. At any condition, it is possible to take a picture of upper hemisphere and to measure SVF with a few seconds by Theta. In the field situation, this function is very important. In the case of FC-E8/9, a few minutes are necessary for preparation of a tripod and setting of the horizontal level.

Only difficulty is the processing from cylindrical projection to equal-area projection, which can be possible by the R program shown in this study.

Theta is made of two fisheye lenses which face opposite directions. Two fisheye images are converted to give the spherical image recorded as the cylindrical equidistant image for the record. The outer edges of the two fisheye images are converted as the adjacent two lines of pixels in the cylindrical image and we sometimes observe small gap of the two lines. But practically, the conversion is so excellently done that it has almost no influence on the SVF measurement considering the comparison in Fig. 8.

4.2 About the R programs

The advantage of using the R programs is that automatic processing of many images is possible at once. In the continuous measurements by Theta, thousands of images should be automatically processed for conversion of the projection, making binarized images, and calculation of SVF. Or in deciding the proper threshold value described in section 3-4, we can compare multiple binarized images with many threshold values automatically made by the program.

Although R is used as the programming language in this study, it is possible to use other language like Python, C, Fortran etc. for the calculation of equations (1)-(8) and Fig. 2.

The algorithm calculating the SFV in this study is based on the pixel counting of the equal-area fisheye image. By Hämmerle et al. (2011) and Middel et al. (2017), the method underestimates the value of SFV in the mid-range compare to the methods shown in Steyn (1980) and Holmer et al. (2001). The difference is actually the usage of the pixel weighting by Lambert’s law.

In the R programs, it is possible to understand the algorithm difference and to add the pixel weighting by Lambert’s law.

5. Conclusion

Applicability of the spherical camera, Theta to the measurement of SVF is tested by comparing with conventional fisheye cameras, FC-E8 and FC-E9. Theta can take the same quality of fisheye images as conventional fisheye camera and can be applied to the measurement of SVF. Accuracy is almost the same considering the influence of the threshold value. As a conclusion, the spherical camera has enough performance for the replacement of conventional cameras.

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