Measuring the scattering in the atmosphere by means of fish-eye photograph of green laser beam

Version 10.2.2022

Contents

1. Pre-processing the RAW images

The RAW-images have to be converted to standard PGM-files (1:1 screenshots of 16-bit values of all pixels of the sensor, RGB pixels covered by Bayer mask are visible). PGM files can be viewed using *IrphanView*, for example. The conversion can be made using *DCRAW* software by commands (%1 means the name of the RAW image):

```
REM Next row produces PGM
DCRAW -E -4 -W -j -t 0 %1
REM Next row produces TIFF
DCRAW -E -4 -W -j -T -t 0 %1
```

Two equivalent PGM and TIFF files are produced. TIFF allows for editing/measuring the RAW pictures in standard photo-editing software (PhotoShop, Corel PhotoPaint, GIMP, …). PGM files are used for the analysis of the light scattered from laser beam.

A cut from a typical pre-processed picture is in Fig. 1.

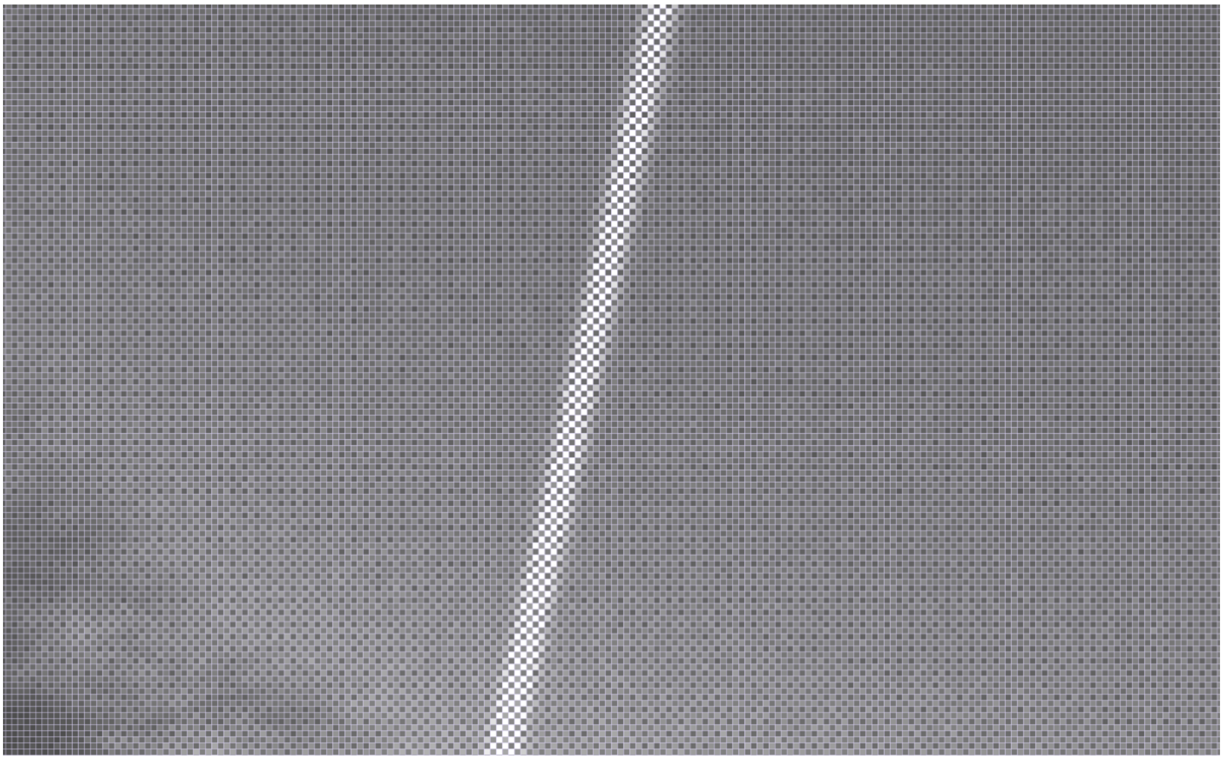

Fig. 1. A cut from a pre-processed picture of a laser beam. Bayer mask is clearly visible.

2. Finding the geometry of the sensor

2.1 Finding the position of the central pixel and the radius of circular image of the sky

The position of the central pixel and the radius of circular image of the sky are basic parameters needed at mapping the position on the sky to the position on the chip. As these values can slightly vary (usually less than 1%) also after removing and reconnecting the lens, or after manipulating the lens focal length, they can be specified later in the configuration file of the software. The calibration curves are automatically adjusted for small changes in the radius of the figure by the software.

For finding the upper-down and right-left borders of the circular image the day-sky pictures are very suitable, as they provide very good contrast between the circular image and the non-illuminated part of the sensor. Fig. 2 shows such a pre-processed picture. The figure is scaled down, so the Bayer mask is not visible (but is present).

Fig. 2. A picture suitable for finding the upper end of the circular image.

The central point and the radius can be easily found by averaging/subtracting the borders. Typical values for Canon EOS 6D Mark II with EF8-16mm fish-eye lens at f= 8mm are:

Xs = 3231 pixels

Ys = 2139 pixels

R = 1990 pixels

The radius of the circular image and its position on the sensor can be easily found also during the calibration of the camera (see later) using point light source – the goniometer has to be set to +/- 90 degrees in horizontal and vertical direction and the position of the light source on the image can be directly read from pre-processed TIFF images.

Last possibility to obtain the radius is directly from the images of the laser beam: set the radius to the value that results in the maximum observed scattering angle close to 180 degrees.

2.3. Finding the position of "dark" pixels

Many sensors have parts covered by opaque material. These pixels can be used for finding the "dark level". If the sensor has no such pixels, a part of the sensor outside the circular image can be used by the same way.

For example, Canon sensors have covered pixels on the top-side and on the left-side (Fig.3):

Fig. 3. Covered pixels on the Canon-sensor on the top-side and on the left-side

Measure the position and size (in pixels) of these two rectangular areas and write down these numbers in form xmin, xmax, ymin, ymax. For Canon EOS 6D Mark II sensor they are:

1, 6382, 5, 41

1, 118, 44, 4222

In the case that the sensor has no covered pixels, specify two rectangular areas in the part outside the circular image.

2.4. Finding the position and size of the picture

Measure the position and the size of the real picture (uncovered pixels). Write down these values in the form xmin, xmax, ymin, ymax. If the sensor has no covered pixels, xmin=0, ymin=0, xmax=xresolution – 1, ymax=yresolution – 1. For Canon EOS 6D Mark II these values are:

120, 6383, 44, 4223

2.4. Finding the position of the Bayer mask

The last step is finding the position of the Bayer mask. Take a test-picture (pure red area displayed on the computer screen). Adjust the focal length of the lens (or change the lens), so the left upper corner of the picture contains red area.

Zoom-in the pre-processed TIFF image. The upper-left corner of the picture looks like in the next illustrative picture (Fig. 4):

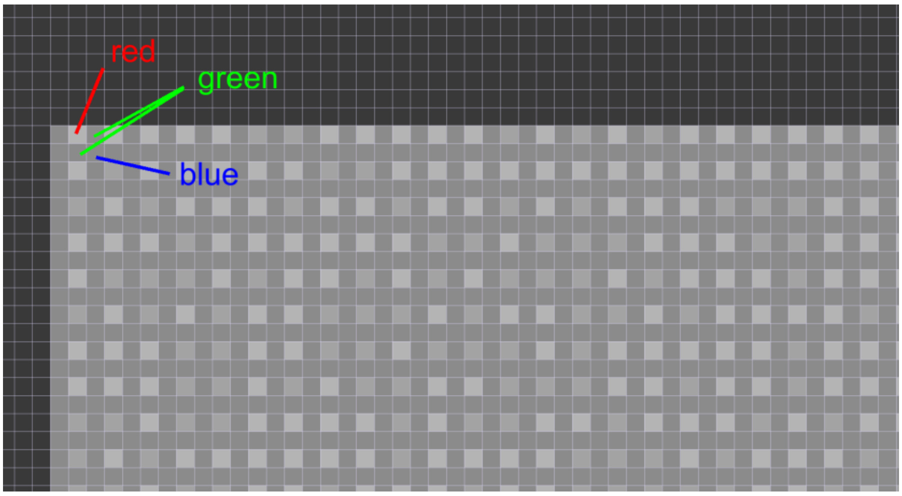

Fig. 4. Illustration of the upper-left corner of the picture. Red pixels are bright.

Red pixels are bright. For situation shown in Fig. 4, the offsets of the Bayer mask are:

x-offset = 1

y-offset = 0

For Canon EOS 6D Mark II are both offsets equal to 0 (relative to the upper-left point of the picture [120, 44]).

Write down these values.

3. Calibrating the camera

The camera has to be calibrated for:

- The relative sensitivity (1 is on the axis of the camera lens) as a function of the incident angle.
- The relation between the position of the pixel on the sensor and the incident angle of input rays.

3.1. The relative sensitivity of the camera

The relative sensitivity is usually applied by the use of a flat-field (homogenously illuminated) picture. However, for the fish-eye pictures a homogenous nearly 360° light source is needed. Such light sources are not very common, so an alternative approach has to be used.

For the alternative approach we need:

- A surface source of the light (output port of an integration sphere, white screen of a phone or similar)
- A goniometer for setting the orientation of the camera (e.g. robotized iPANO mount).

The light source should be placed on the axis of the camera lens in the distance much higher than the size of the camera (e.g. 5m). Afterwards a set of pictures have to be taken for various incident angles (e.g. in 5° steps). The angular dependence of recorded intensity can be found from pre-processed TIFFs. The angular dependence of the sensitivity for Canon EOS 6D Mark II + EF8-16mm fish-eye at f=8mm lens is in Fig. 5.

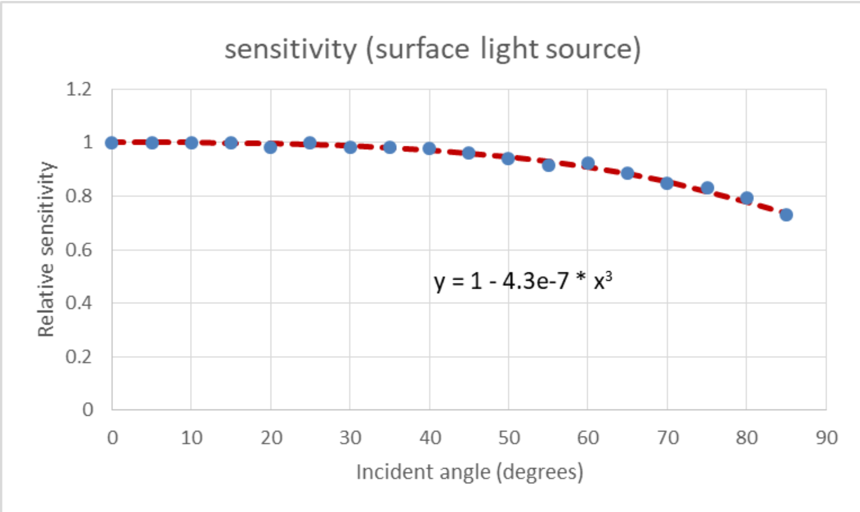

Fig. 5. Angular dependence of the sensitivity of a Canon EOS 6D Mark II camera with EF8-16mm fish-eye lens at f=8mm.

3.2. The relation between the position of the pixel on the sensor and the incident angle (linearization of the position)

The same steps as in 3.1 are to be followed, however, a point-like light source (e.g. LED) has to be used. The relative position of the light source (according to the centre of the picture) can be tracked using pre-processed TIFF images. The dependences radius-angle and angle-radius of a Canon EOS 6D Mark II camera with EF8-16mm fish-eye lens at f=8mm is shown in Figs. 6 and 7.

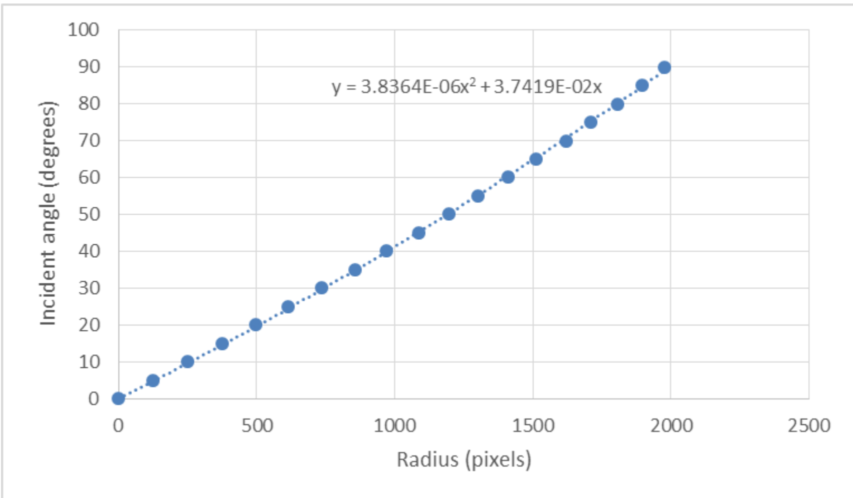

Fig. 6. The dependence of the incident angle on radius.

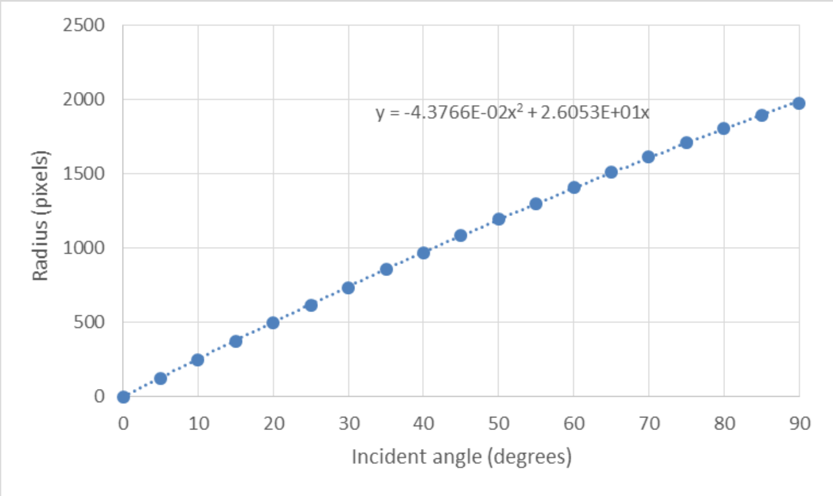

Fig. 7. The dependence of the radius on incident angle.

Both direct and inverted fitting curves are used later in the software.

3.3. Modifying the 'green_laser' software

All three calibration functions (sensitivity and linearization – see Sections 3.1 and 3.2) have to be implemented into 'Sensitivity()', 'R2thetadeg()' and 'Thetadeg2r()' functions:

```
float R2thetadeg(float r)
{
    //our Canon EOS 6D MarkII s Fish eye 8-16 mm
    r*=1990.0/(float)rmax; //1990 - the radius found at the calibration
    return 0.037419*r+3.8364e-6*r*r;
}

float Thetadeg2r(float thetadeg)
{
    //our Canon EOS 6D MarkII s fish eye 8-16 mm
    float r = 26.053*thetadeg - 0.043766*thetadeg*thetadeg;
    r*=(float)rmax/1990.0; //1990 - the radius found at the calibration
    return r;
}

float Sensitivity(float thetadeg)
{
    //our Canon EOS 6D MarkII s fish-eye 8-16mm
    if(thetadeg>90.0) return 1; //out of image
    else
    {
        float sens=1 - 4.30e-7*thetadeg*thetadeg*thetadeg;
        return  sens;
    }
}
```

The position of the covered pixels (see Section 2.3) are to be written down into the ‘border’ variable:

```
int border_no=2; //number of covered areas
```

```
long border[2][4]={{1,6382,5,41},{1,118,44,4222}};
//xmin,xmax,ymin,ymax
```

The position of the picture (without covered pixels – see Section 2.4) is to be written down into the ‘picture’ variable:

```
long picture[4]={120,6383,44,4223}; //xmin,xmax,ymin,ymax
```

The offsets of the Byer mask are to be stored into ‘maskoffset_x’ and ‘maskoffset_y’ variables:

```
long maskoffset_x=0,maskoffset_y=0;
```

So, the ‘green-laser’ software must be specially compiled for each camera/lens combination.

4. Field measurement

4.1. Setting-up the camera

Camera should be oriented directly to the zenith. Use a level placed on the cover of the lens. Be precise! The azimuthal orientation of the camera should be set by such a way, that the bottom of the camera is oriented toward the laser (the laser path starts on the bottom of the captured image). The azimuthal orientation is not very critical part at the setting the camera.

4.2. Setting-up the laser

For the scattering phase measurement the distance of the laser should be about 100-150 m (or similar). Measure the distance using laser distance meter or a type measure. Write down the measured value. For vertical dependence measurement the distance of the laser should be about 500 m (or similar). Measure the distance using laser distance meter or using Google maps, if a fine picture of the area is available.

Set the laser horizontally using a level and write down the angle that corresponds to the horizontal orientation (or set the scale to zero). Then aim the laser beam directly on the camera (be careful not to hit people near the camera) and write down this base angle (the terrain is not perfectly flat). Then point the laser 10-20 degrees over the camera and write down this value (elevation). For vertical measurement point the laser 90 degrees from the horizontal orientation.

4.3. Setting-up the exposure time and ISO

Set the exposure time and ISO to high values. Check that the picture is not overexposed. Typical exposure times (ISO 1600 – 3200) for scattering phase function measurement is 10-20 s, for vertical dependence the typical exposure time is 30s – 2min.

4.4. Measurement

Take the picture of the sky with the laser beam. Afterwards take the picture of the sky with the laser turned off. Both images are processed in the same way, so the difference of extracted data can significantly suppress the background. If no background image was taken, the software will subtract the sky from parts of the picture next to the laser path, this can be sufficient.

5. Processing the pictures

5.1. Converting RAW to PGM

Typical picture (the azimuthal orientation of the camera is set not very well but it is no problem) taken in the night is shown in Fig. 8:

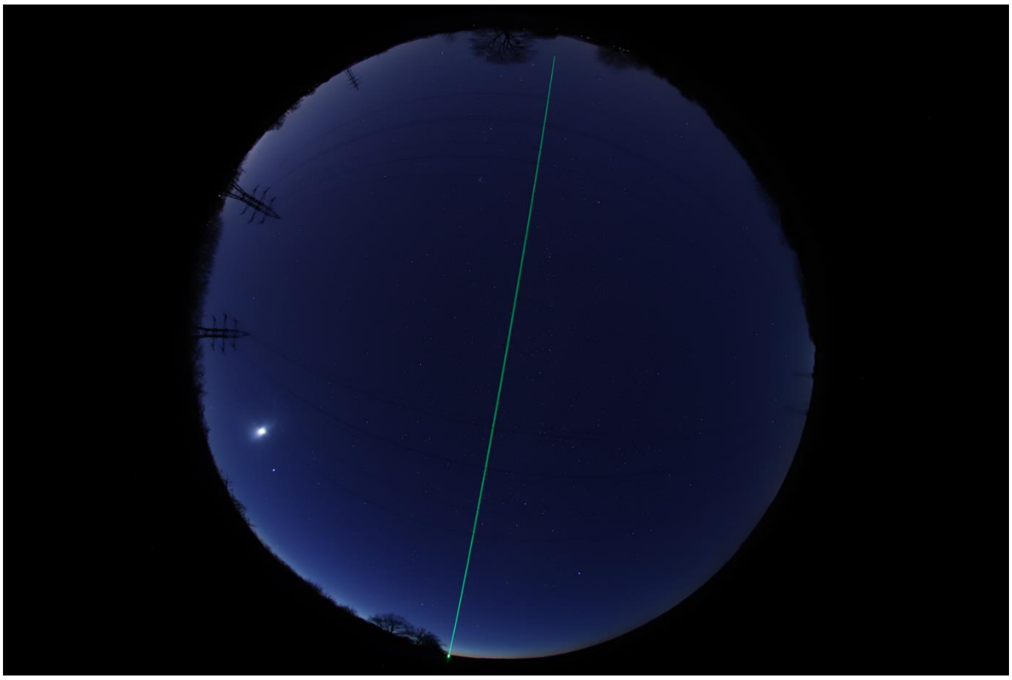

Fig.8. Colour photograph of the laser beam

Using DCRAW (See Section 1) we get pre-processed PGM and TIFF images (Fig. 9):

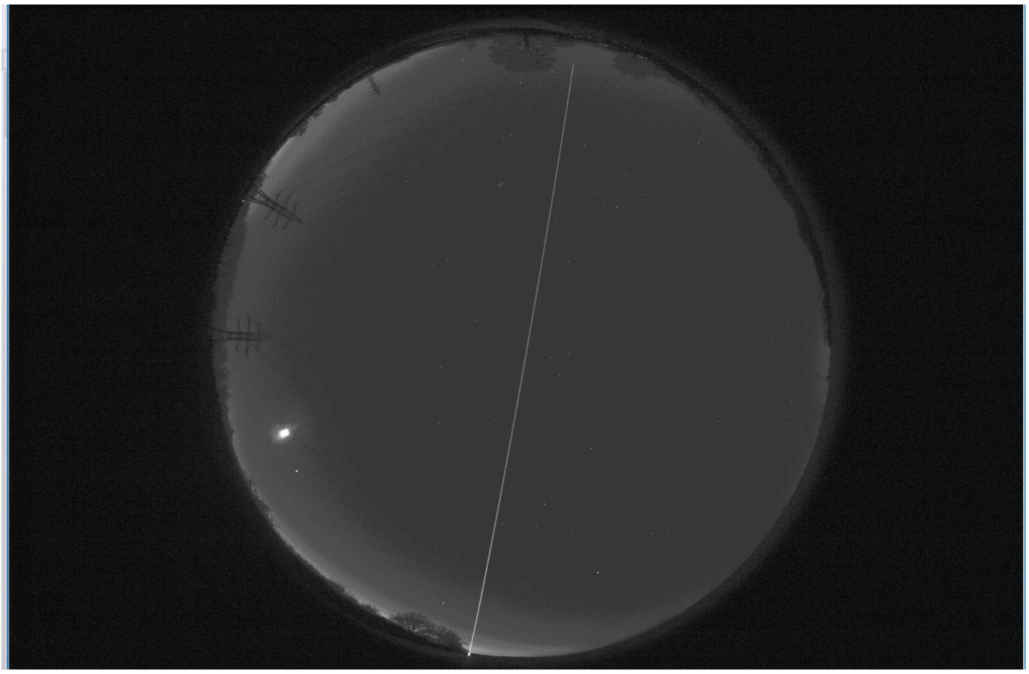

Fig. 9. Pre-processed image

5.2. Digitizing the path of the laser beam

The positions of the laser beam (in pixels) should be manually stored in 'greenlaserpath.txt' file. Usually ca 10 points are enough. The positions can be read from a standard photo-editing software. Be precise in finding the centre of the beam (Fig. 10). Be sure that both ends of the beam are stored, mainly the centre of the laser (where the laser beam started). This point is used as a reference point for elimination the inclination of the terrain.

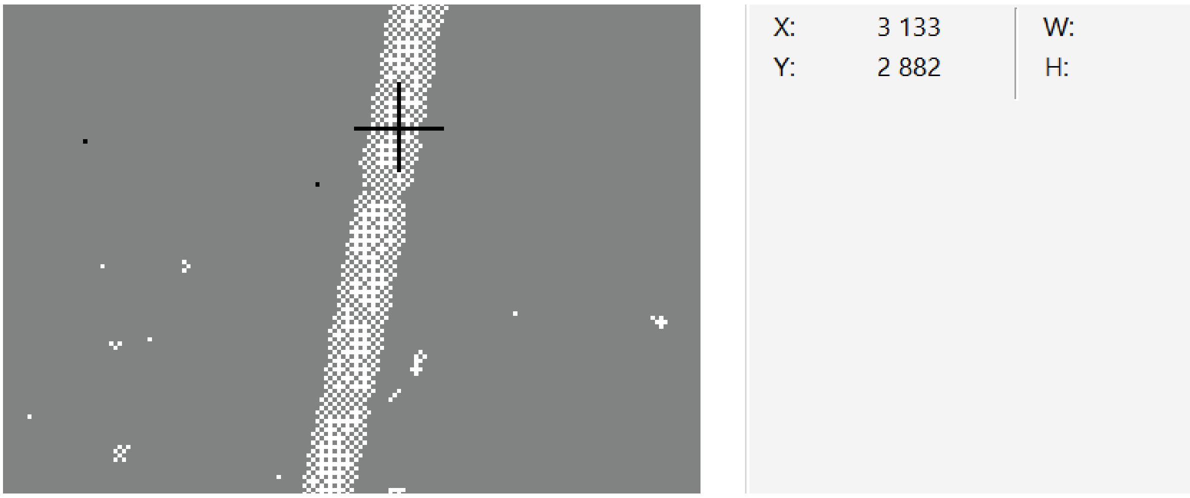

Fig. 10. Digitalizing the path of the laser beam

Typical content of the 'greenlaserpath.txt' file is as follows:

```
2895 4096
2928 3942
2955 3811
…
3552 375
```

5.3. Configuring the 'green-laser' software

The parameters of the extraction can be set in 'greenlaserconfig.txt' file. Its typical content is:

```
IMG_4120.pgm
IMG_4121.pgm

150
10

26
3
50

3000
300

3276
2147
2044

Help:
Write following twelve parameters:
```

```
1 = filename of the PGM-picture of the laser beam.

2 = filename of the PGM-picture with the laser beam turned off. Use NODARK
if no background picture was taken.

3 = Distance laser-camera in meters.

4 = Elevation of the laser in degrees.

5 = Width (in pixels) of the band that covers the beam (see
linearlyscaledG.pgm)

6 = How much are side bands (background) wider than laser band (see
linearlyscaledG.pgm)

7 = Median filter width (use 0 for no median filtering)

8 = level_limit (>1). All levels in photograph, which are higher than
level_limit are replaced by level_limit. This partly suppress the effect of
extremly high levels (stars, artifical light sources, ...). See
"corrected.PGM" file to check the proper level. Use value of 0 for no
correction.

9 = size of the centre. size of the square area of the picture where the
average RGB levels are calculated.
For photos of integration sphere anything between 100-1000 is OK.

10 = x-position of the centre of the circular picture on the chip in pixels
(this and next numbers can slightly vary from camera to camera or from day
to day - check photos of a day-sky for example).

11 = y-position of the centre of the circular picture on the chip in pixels

12 = radius of the circular picture on the chip in pixels

The position of the centre of the fish-eye picture and its radius can
slightly depend on the camera used.
For our camera+ fish-eye they are:
xs = 3223
ys = 2154
R = 2012
For Stephan's camera:
3224
2154
1990
```

The meaning of the parameters is:

1st row – name of the PGM file containing the photograph of the laser beam.

2nd row – name of the PGM file containing the photograph of the sky without the laser beam. If 'NODARK' is used as a filename, no background image is substracted.

3st row – distance between laser and camera (see Section 4.2)

4th row – elevation of the laser camera (see Section 4.2)

5^{th} row – width of the band (in pixels) that covers the laser beam. In generally, the band should be only slightly wider than the beam, otherwise more bright stars falls into the band and increased noise can be seen in extracted data. The position of the band can be checked in 'linearlyscaledG.pgm' file generated by the 'green_laser' software (see later). For the situation shown in Fig. 10 the value of 20 – 30 is adequate.

6^{th} row – the multiplication coefficient (how much wider should be the right and left bands for background level subtraction). In generally, wider bands result in less noisy result. The bands can be checked in 'linearlyscaledG.pgm' file generated by the 'green_laser' software (see Section 5.4).

7^{th} row – width of the median filter that is applied to the extracted data. This filter dramatically suppresses the noise. However, fine details are lost after the filtering. Set this value to get the best details/noise ratio. Use value of 0 for no median filtering. Don't worry, the software outputs both non-filtered and median-filtered extracted data.

8^{th} row – signal level limit. The signal levels are usually very low in comparison to the dynamic range of the PGM picture (65535). This results in very dark picture that need brightness adjustment in the viewer. If other value than 0 (no limit) is written, all signal values are linearly scaled (level -> 65535). This influences only 'linearlyscaledG.pgm' file, this setting has no influence on extracted data.

9^{th} row – size of the central part of the picture, where average red/green/blue levels are calculated. This setting doesn't influence the extracted data, the averaged values only give the idea about signal levels close to the zenith.

10^{th} – 12^{th} row – x, y position of the centre of the circular picture of the sky and its radius (all values in pixels). These values are known from the calibration phase, however, they can be regularly checked (see Section 2.1).

5.4. Running the 'green_laser' software

The processing of the PGM pictures starts by starting the 'green_laser' software. The following procedure starts:

- The configuration file and the digitalized path of the laser beam are read. Both image files are opened and processed the same way.
- Dark – levels (red/green/blue) are found from covered pixels. These values are subtracted from all signal pixels.
- Average signal levels close the zenith are calculated (only for your information).
- The laser beam is traced pixel-by-pixel in the y-direction. The positions of the beam are found from digitized data by linear interpolation.
- For each row (y – value of the laser beam path) the green channel is processed by the following way:
    - Signal from the background image (if available) is subtracted.
    - The sensitivity correction is applied (see Section 3.1)
    - The median of signals from side-bands is found. The median suppress the signal from bright stars located in the side-bands. The median is much more effective than an average in such situation.
    - The integral value (sum) of signals from pixels within the inner band are calculated after subtraction of the median value of the background.
    - The extracted integral value of the signal from green laser is stored.

- The distance from camera to the laser beam, the height of the laser beam, the zenith angle and the scattering angle are calculated and stored (see Fig. 15). The zenith angle is corrected for terrain inclination (zenith angle of the laser itself is set to 90 deg). This correction is not applied for vertical distribution measurement.

- For your information, 'linearlyscaledG.pgm' file is created. The figure shows the green channel of the processed picture. The positions of the central band and both side-bands is also shown. Check that the width of the bands (see the description of the configuration file above) is set properly (Fig. 11). If NODARK is set (no background image is available), created PGM picture is based on the laser beam image without the background image subtraction.
- Extracted data contains a lot of "spikes" (Fig. 12) caused by:
    - The occasional presence of a bright star directly behind the laser beam
    - The occasional presence of dark object (e.g. power lines in our case)
- So, the median filter is applied to the extracted data (see configuration file description above). This filter dramatically suppresses the noise. The filtered signal is scaled to 1 at the scattering angle of 90 degrees (see Fig. 13).
- Basic analysis of extracted data is made – a product of the signal and the sine of the scattering angle is calculated (Fig. 14). The signal is also influenced by the extinction. Such correction is not applied and has to be done afterward by the user, if needed.
- The output 'green_laser_data.txt' file is written (see next section).

Fig. 11. A cut from 'linearlyscaledG.pgm' file. The laser beam is located in the central band. Both side-bands are also shown. A few power lines crosses the image of the laser beam. No background image subtraction was applied.

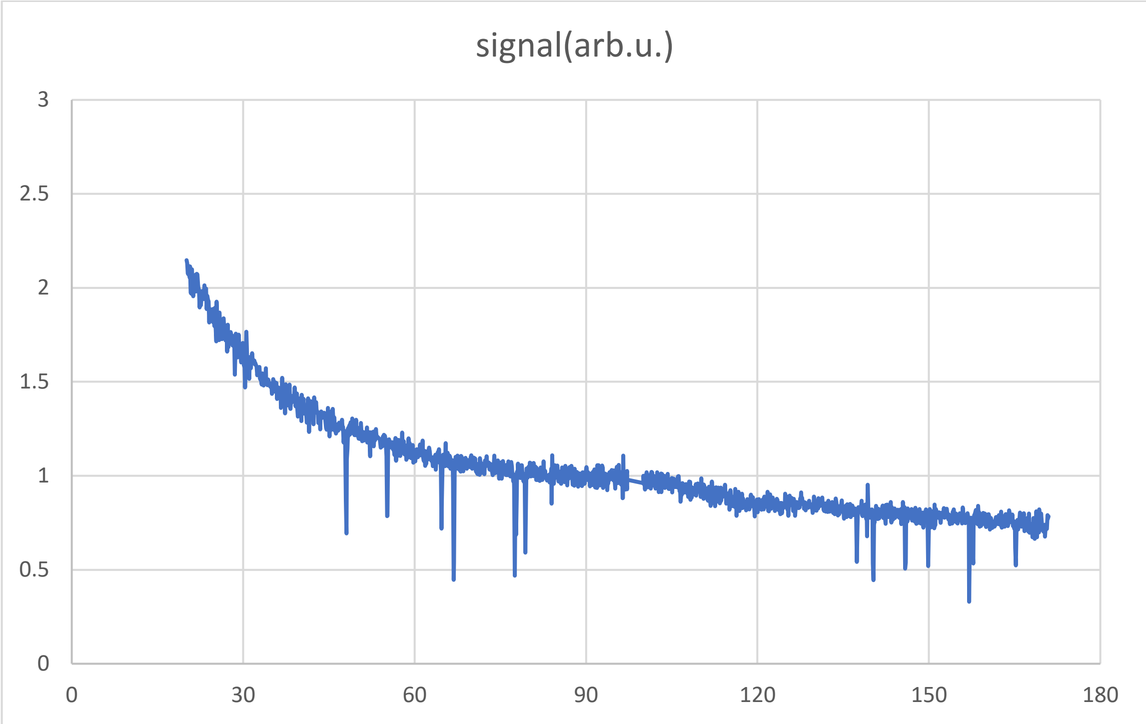

Fig. 12. Extracted signal for scattering angles 20 – 170 degrees. Spikes from stars (up) and from the power lines (down) are present.

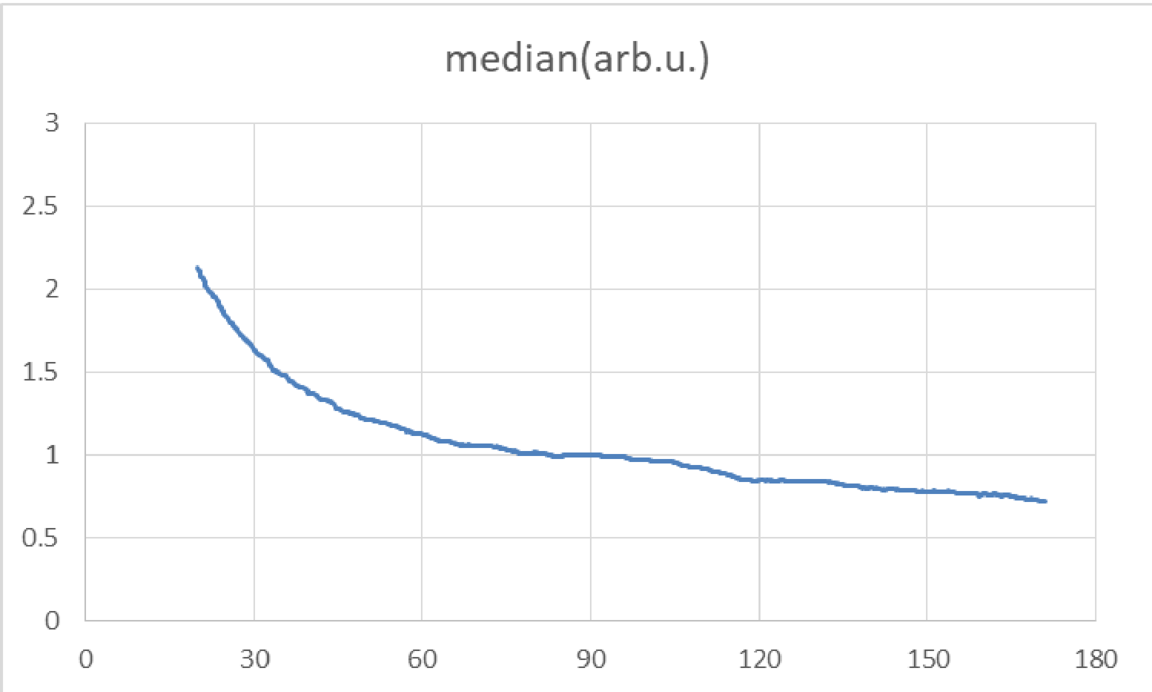

Fig. 13. Median-filtered data.

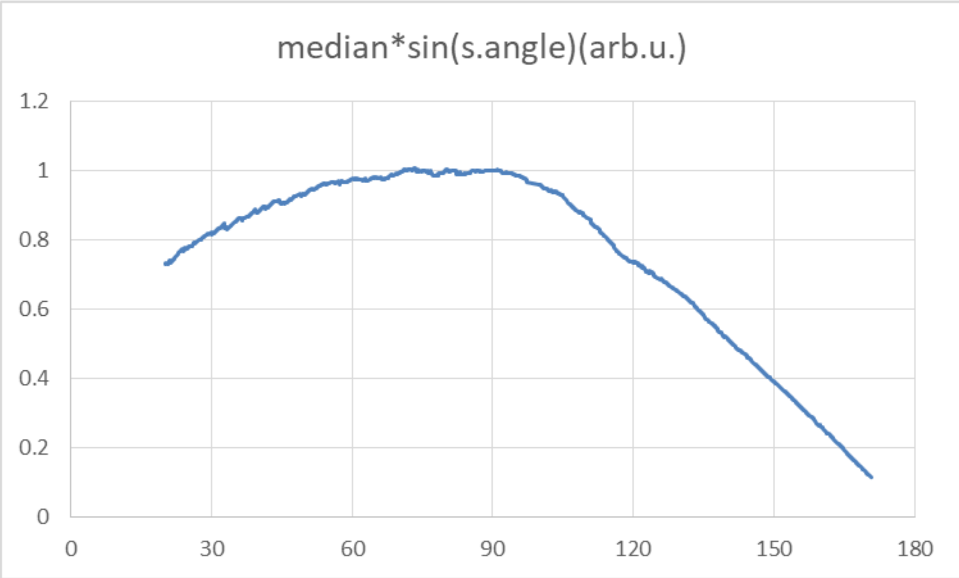

Fig. 14. The product of the signal and the scattering angle

5.5. The output file 'green_laser_data.txt'

The structure of the output file is as follows:

x(pixel) y(pixel) r(pixel) z.angle(deg) s.height(m) s.distance(m) s.angle(deg) signal(arb.u.) median(arb.u.) median*sin(s.angle)(arb.u.)

3552	375	1808.98	-78.8316	247.417	1277.36	178.832	0.142214	0.142214	0.00289995
3551	377	1806.84	-78.7214	228.3	1167.3	178.721	0.385024	0.382649	0.00853847
3551	379	1804.87	-78.6205	213.481	1081.98	178.621	0.382649	0.385024	0.00926897
…									
2895	4095	1968.69	89.9482	0.13489	149.235	10.0518	27.0657	27.0657	4.72401

The numbers have following meanings:

- X(pixel) – x-position of the laser beam on the picture
- Y(pixel) – y-position of the laser beam on the picture
- R(pixel) – radius-position of the laser beam (distance from the centre if the image)
- Z.angle(deg) – zenith angle in degrees
- S.height(m) – the height of the laser beam in meters
- S.distance(m) – the distance between the laser beam and the camera in meters
- S.angle(deg) – the scattering angle in degrees
- Signal(arb.u.) – extracted signal from the green laser
- Median(arb.u.) – median filtered signal from the green laser
- median*sin(s.angle)(arb.u.) – processed data for further calculations

For scattering phase function measurement should be the maximum positive value of the zenith angle equal to 90 deg (minimum scattering angle = elevation of the laser) and maximum scattering angle at the end of beam should be very close to 180 deg. If it is not true, change (calibrate) the radius-parameter (see Section 2.1).

For vertical distribution measurement should be the minimum scattering angle about 90 deg (depends on the inclination of terrain) and maximum close to 180 deg (maximum zenith angle close to 90 deg).

6. Some geometrical relations used in the software

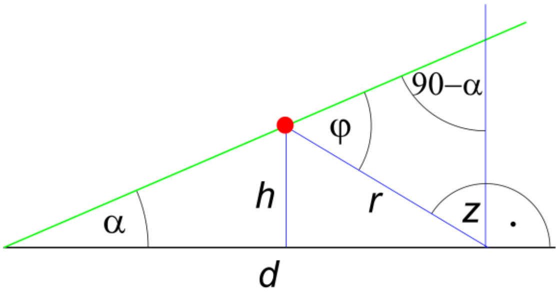

Fig. 15. The description of the parameters. *d* – distance between the laser and the camera, α – elevation angle, *z* – zenith angle, φ – scattering angle, *r* – distance between the scattering point and the camera, *h* – height of the scattering point

$$\varphi = 90 - z + \alpha$$

$$r = \frac{\sin\alpha}{\cos(z-\alpha)} d$$

$$h = r\cos z$$