ACCURACY EVALUATION OF THE RADIOMETRIC DISTORTIONS FILTERING METHODS

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1. Introduction

By the use of digital photogrammetric approach monotonic work of geodesy experts became easier. Acquisition of data became faster, quantity of human mistakes lower. This influences time and costs needed work to be done.

Demand of the geodetic data rises each year. Orthophoto images are renewed each year in many European countries. Dynamic and in time renewed data are needed all over the world. Such requirements can be satisfied only if newest digital technologies will be applied.

Because of the very big amount of the geodetic data, fully digital technologies started their work in the map and geodetic data production field just 6-7 years ago. However new problems aroused together with new technologies. One of the problems need to be solved is quality and radiometric continuous of the aerial photographs – the primary photogrammetric data. The problem rises because of radiometric distortions of the aerial images.

To improve the aerial photographs the forward motion compensation mounts, gyrostabilizers and very high accuracy optic systems are used. During a scanning process aroused problems can be solved by using different types of calibration. However such equipment can’t protect images from different optical phenomenon. One of those is the “hot spot” phenomenon [1, 2].

Usually we can meet the hot spot phenomenon in earth surface photographs. That is a phenomenon when the brightness of a photograph uniformly changes from one side (or part) to another (Fig. 1). It is noticed that the color distortion depends on the position of the sun at the time when a photograph is taken.

Such radiometric distortions make difficult automatic point recognition and measurement during aerial triangulation process, pervert radiometric continuous of the orthophotos, cause difficulties during photointerpretation. Here we can see the removal of radiometric distortions is very important part of the digital geodetic data acquisition process.

2. Radiometric equalization methods of the orthophotomaps

Radiometric difference of the aerial photographs and the hot spot phenomenon causes a big jump of the mean color in the area of photographs jointing. Orthophoto production systems try to solve this problem by applying various algorithms of the radiometric equalization.

2.1. Moving of jointing limits

One of the methods is to hide color jumps by moving jointing limits to another places, such as rivers, roads or limits of plots (Fig. 2). This method is used in
the commercial software [3], but it is not good enough. It can cause erroneous interpretation of the visual information in that area of an orthophotomap because the same kind of crops or areas will have a different color.

![Figure 2](image)

**Figure 2.** A jump of the mean color in the area of photographs jointing. *a* – before edition, *b* – after manual edition of the jointing

### 2.2. Combining images by changing juncture point line by line

A typical method of generating "seamless" mosaics of digital image sections is described in [4]. The method has four steps. In the first step, the image sections are brought to aerial triangulation (geopositioning, registration).

Once the overlap region has been identified on the registered images, the gray level of one of the images, L or R (left or right), is adjusted linearly until the average gray level in the overlap region of image L matches the average gray level in the overlap region of image R. This completes the second step: the output image still shows the seam but it is substantially less visible.

In the third step a feathered seam is created. On a line by line basis, a juncture point is chosen; the picture information in the final mosaic to the left of the juncture point will come from the line segment of image L, and image R will supply the rest of that line in the mosaic. Define

\[
D(n) = \sum_{i=-w/2+1}^{i=w/2} |L(n + i) - R(n + i)|
\]

where \(L(j), j = 1, 2, \ldots, K\) are the gray-level values of the current line in the overlap region of image L. Similarly, \(R(j), j = 1, 2, \ldots, K\) for R. Naturally, a value for the parameter \(w\) must be less than the width of the overlap region. To find this line's juncture point, one finds the value of \(n\) that minimizes \(D(n)\). This method finds a succession of juncture points, one per line, with horizontal positions that are unrelated to each other. A refinement of this algorithm constrains the juncture point of a given line to be near those of adjacent lines.

This and similar methods of the radiometric equalization are used at the end of the geodetic data production process during generation of orthophotos. The available methods don’t seek to remove distortion, but are oriented to adjust radiometric characteristics of the images and to obtain a good seem of the final product. However, radiometric distortions can affect quality of the final product in early stages such like automatic recognition of tie points. The hot spot phenomenon makes difficulties for such recognition also.

The papers [1, 2] propose to make radiometric filtering methods just after the scanning process before to start geometric equalization.

### 2.3. The images averaging method

The method proposed in [1] is based on images averaging. Because the position of the sun changes for a very small distance during taking photos for one strip (or more strips if they are short), it can be assumed that the center of the hot spot is in the same position for all
photographs in this strip. For that reason removal of the interference can be achieved by averaging a few images of the same strip. Accidental changes of the hue will eliminate each other and the hot spot component will grow up because it is recurrence.

Few photographs per strip are chosen and these chosen images are reduced using the Nearest Neighbor method. These new small images are used to create a mean image. Pixels for the mean image are calculated according to the following equation:

\[
R_{vmn} = \frac{1}{N_F} \sum_{i=1}^{N_F} R_{imn},
\]  

(2)

where \(m\) is the index of the line, \(n\) is the index of the column, \(N_F\) is the number of the used photographs.

To obtain better results it is advisable to use as much as possible photographs. Absolute accuracy of the hot spot hue distribution would be obtained by using infinity photographs \(N_f \rightarrow \infty\). However, the mean image obtained by using a final number of the photographs describes radiometric distortions caused by the hot spot phenomenon as well.

To create the mathematical model of the hot spot, the approximation by the second rank polynomial is used:

\[
R_M = x_1 m^2 n^2 + x_2 m^2 n + x_3 m n^2 + x_4 m^2 + x_5 n^2 + x_6 m n + x_7 m + x_8 n + x_9,
\]  

(3)

The coefficients \(x_i\) should be calculated using the equation system which contains nine equations created according to (3). The values of the variables \(r_{Mn}\) for each equation are mean colors of pixels and are taken from the chosen points of the mean image. These points are chosen evenly in all area of the mean image (see Fig. 3). The points, which are close to the sides, should be chosen with a little distance (for example, 5% of the edge length) from the edges of the image. This is because the external part of the picture can contain a black diapositive frame, which remains after scanning. This frame doesn’t have any useful information.

After the equation system is solved, the mathematical model of the hot spot distribution can be obtained. For that purpose the mean color \(r_{vid}\) of the mean image should be calculated:

\[
r_{vid} = \frac{1}{l \cdot l} \sum_{i=1}^{l} \sum_{j=1}^{l} R_{imn}.
\]  

(4)

To recalculate the radiometric data of the initial images and other photographs of the same strip the following equation is used:

\[
r'_{mn} = r_{mn} + r_{vid} - r_{Mmn},
\]  

(5)

where \(r'_{mn}\) and \(r_{MN}\) are the radiometric values of the initial and equalized images, \(r_{Mmn}\) is the color of the hot spot model for the pixel that is analyzed. The color is calculated using equation (3).

![Figure 3](image_url)

The described [1] images averaging method allows evaluating and removing color distortions caused by the hot spot phenomenon. However the accuracy of the method depends on the quantity of the used images and on the distribution of the color objects in these images.

2.4. Application of the standard low-pass FIR filters

The radiometric distortion of the aerial photograph caused by the hot spot phenomenon corresponds to a very low spatial frequency in frequency domain. Therefore, it should be possible to extract the shape of the distortion using low-pass Finite Impulse Response (FIR) filters [2, 5, 6, 7, 8, 9].

A common way to design FIR filters includes:
• The passband and the cutoff frequency – the frequency response of the filter determination.
• An ideal (infinite) impulse response calculation.
• The infinite impulse response truncation, by applying a window.
• Verification of the designed filter frequency response.

This workflow is suitable for one-dimensional FIR filter and for spatial (two-dimensional) FIR filter design as well. However, we need to obtain a two-dimensional impulse response for images filtering. This can be done by transforming a one-dimensional FIR filter into a two-dimensional FIR filter (the frequency transformation method) or by designing the filter in two-dimensional manner through the all design steps.

The frequency transformation method [6] generally produces very good results, as it is easier to design a one-dimensional filter with particular characteristics than a corresponding two-dimensional filter.

If the desired frequency response is

$$H(e^{j\omega}) = \left| H(e^{j\omega}) \right| e^{j\arg(H(e^{j\omega}))},$$

then we calculate the ideal impulse response by applying the inverse Fourier transform:

$$h(n) = \frac{1}{2\pi} \int_{-\pi}^{\pi} H(e^{j\omega}) e^{j\omega n} d\omega,$$  \hspace{1cm} (7)

where $\omega$ is the frequency of the digital signal, $0 \leq \omega \leq 2\pi$, $n$ is the index of the digital signal sample or the index of an image pixel in a line or a column.

To obtain a finite impulse response filter, the infinite impulse response $h(n)$ should be truncated by applying a window $w(n)$:

$$h_f(n) = h(n)w(n).$$

There are several types of the windows that can be used for the FIR filter design: Boxcar (a rectangular window), Hamming, Hanning, Bartlett, Blackman, Kaiser, Chebyshev, Triangular. For more details see [5, 6, 7].

To verify the frequency response of the truncated filter, the Fourier transform should be applied:

$$H(e^{j\omega}) = \sum_{n=-\infty}^{\infty} h(n) e^{-j\omega n}. \hspace{1cm} (9)$$

If the calculated frequency response fits to the requirements, then the two-dimensional filter can be produced by applying the frequency transformation method. The method transforms a one-dimensional FIR filter into a two-dimensional FIR filter. The frequency transformation method preserves most of the characteristics of the one-dimensional filter, particularly the transition bandwidth and ripple characteristics. This method uses a transformation matrix, a set of elements that defines the frequency transformation. Usually the McClellan transform matrix is used [4]:

$$t = \frac{1}{8} \begin{pmatrix} 1 & 2 & 1 \\ 2 & -4 & 2 \\ 1 & 2 & 1 \end{pmatrix}. \hspace{1cm} (10)$$

The transformation below defines the frequency response of the two-dimensional filter:

$$H(e^{j\omega_x}, e^{j\omega_y}) = B(e^{j\omega}) \bigg|_{\omega_x=\omega,\omega_y=\omega} \hspace{1cm} (11)$$

where $B(e^{j\omega})$ is the Fourier transform of the one-dimensional filter $b(n)$,

$$B(e^{j\omega}) = \sum_{n=-N}^{N} b(n) e^{-j\omega n} \hspace{1cm} (12)$$

and $T(e^{j\omega_x}, e^{j\omega_y})$ is the Fourier transform of the transformation matrix $t$:

$$T(e^{j\omega_x}, e^{j\omega_y}) = \sum_{n_x} \sum_{n_y} t(n_x, n_y) e^{-j\omega_x n_x} e^{-j\omega_y n_y} \hspace{1cm} (13)$$
The constructed filter \( h(n_1, n_2) \) is the inverse Fourier transform of \( H(e^{j\omega_1}, e^{j\omega_2}) \):

\[
h(n_1, n_2) = \frac{1}{(2\pi)^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} H(e^{j\omega_1}, e^{j\omega_2}) e^{j\omega_1 n_1} e^{j\omega_2 n_2} d\omega_1 d\omega_2. \quad (14)
\]

Using the designed two-dimensional FIR filter, an image can be processed (filtered) by applying the two-dimensional convolution:

\[
y(n, m) = \sum_{k=-\infty}^{\infty} \sum_{r=-\infty}^{\infty} h(k, r) x(n-k, m-r), \quad (15)
\]

where \( n \) and \( m \) are the indices of the pixels in columns and lines of an image.

There is shown [2] that the standard linear filtering is not suitable to determine the hot spot model from a single photograph, however, the application of the low-pass FIR filters helps to create and evaluate the radiometric hot spot distortion parameters, to define the distortion position and amplitude.

It is important to find the hot spot center – position of the radiometric distortion to compare the operation of different methods or to use arbitrary standard surfaces for the distortion model approximation. It is quite difficult to do this using just the images averaging method because the brightest pixel of the mean image usually is not a hot spot center. The low-pass filtering is a tool for the detection of such points by evaluating the maximal gray level intensity.

### 2.5. The histogram parceling method

A nonlinear filtering method – “The histogram parceling method” is proposed in [2].

To decrease the influence of the large high intensity areas, histogram of an aerial photograph could be transformed by dividing it into zones – parcels and moving the high intensity parcels to the lower intensity side.

There is proposed to divide histogram into the following parcels of the intensity:

1. Background part \( D_I \). It includes the lower than mean intensities (see Fig. 4). The mean intensity of the aerial photograph has values 100 through 130 usually.
2. Mean intensity part \( D_{II} \).
3. High intensity part \( D_{III} \).

Each parcel of the intensities should be moved to the low intensities side by appropriate distances \( g_{II} \) and \( g_{III} \) for \( D_{II} \) and \( D_{III} \), respectively.

By performing an analysis of different aerial photographs the values for the parcels limits and intensities correction were obtained: \( G_1 = 120; \) \( G_2 = 165; \) \( g_{II} = 55; \) \( g_{III} = 100 \). A little variation \( \pm 5 \) gray levels) of the values doesn’t influence the final results.

To be sure that the processed images fit to the same histogram width, all photographs should be verified and expanded to the full gray level width by applying the linear contrast correction [7, 8, 9]:

\[
a = \frac{255}{B_{m}^{\max} - B_{m}^{\min}}, \quad (16)
\]

\[
b = \frac{255B_{m}^{\min}}{B_{m}^{\max} - B_{m}^{\min}}, \quad (17)
\]

where \( B_{m}^{\min}, B_{m}^{\max} \) are the values of the input histogram width, \( B_{m}^{\min}, B_{m}^{\max} \) are the values of the output (desired) histogram width. The calculated correction parameters \( a \) and \( b \) are used to transform a histogram by equation:

\[
B_{m}^{\text{out}} = aB_{m} + b. \quad (18)
\]
The mean intensity of the image according to Fig. 4 is
\[
I_{\text{avg}} = \frac{1}{MN} \left( \sum_{i=0}^{G_{1}} g_{i} p_{i} + \sum_{i=G_{2}+1}^{G_{3}} g_{i} p_{i} + \sum_{i=1}^{255} g_{i} p_{i} \right). \tag{19}
\]

where \(M\) is the number of lines, \(N\) is the number of columns in the image, \(g_{i}\) – gray level value, \(p_{i}\) – the number of pixels corresponding to the gray level.

The mean intensity after the histogram parceling method application is described by the following equation:
\[
I'_{\text{avg}} = \frac{1}{MN} \left( \sum_{i=0}^{G_{1}} g_{i} p_{i} + \sum_{i=G_{2}+1}^{G_{3}} (g_{i} - g_{m}) p_{i} + \sum_{i=1}^{255} (g_{i} - g_{m}) p_{i} \right). \tag{20}
\]

It is important to take this value into account during radiometric distortion amplitude evaluation.

Because the histogram parceling method and the images summing method work in different ways they can be used simultaneously. Such combined method is investigated in [2] as well.

3. Accuracy evaluation

The described methods are suitable for radiometric distortions neutralization. The ones described in 2.1. and 2.2. chapters don’t pretend to be accurate and are used just for hiding radiometric imbalance between photographs. The methods described in 2.3. throw 2.5. are developed to remove not just a seam but the whole distortion. However, which one is the best it is difficult to say, because there is no method suggested for the absolute accuracy evaluation of the methods in [1, 2].

The position of the hot spot distortion center was calculated by evaluating the maximal gray level intensity in [2]. To compare the obtained results, the standard deviations for each direction (\(x\) and \(y\)) and for the radiometric value of the center position there were calculated:
\[
\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_{i} - \overline{x})^2}. \tag{21}
\]

To evaluate the overall distance from the destination point, the standard deviation vector module was calculated:
\[
\eta_{2D} = \sqrt{\sigma_{x}^2 + \sigma_{y}^2}. \tag{22}
\]

The values of the standard deviations should be as small as possible (equal to zero in the ideal case). It is quite good criteria when the low-pass filtering or the histogram parceling methods are used. If the standard deviations are very small, then we can say we have found the approximate position of the distortion. However, that doesn’t say anything about absolute accuracy of the methods, because the true position of the distortion is unknown and we can’t compare the results. To solve this problem the modeling of the aerial photograph was proposed.

3.1. Modeling of the aerial photograph

According to the experimental results the parabolic dependence of the hot spot distortion was chosen. If the center of the distortion is \(C(m_c, n_c)\) (see Fig. 5) then the radiometric intensity of the simulated image should change according to formula:
\[
r_{i} = r_{a} - b l^2; \tag{23}
\]

where \(r_{i}\) is the calculated value of a pixel, \(r_{a}\) is the value of a pixel in the center of the distortion, \(l\) is the distance from the hot spot center. The distance \(l\) is calculated according to the circles formula:
\[
l = \sqrt{(m - m_c)^2 + (n - n_c)^2}. \tag{24}
\]

Parameter \(b\) is calculated according to the condition:
\[
b = \frac{r_{a} - r_{b}}{R^2}. \tag{25}
\]

Values of the variables \(r_{a}, r_{b}, R\) can be matched using experimental results.
An aerial photograph can be described as a set of flat objects complemented by high frequency noise. That can be modeled using a uniform distribution random number generator. Random numbers are in range [0,1] usually, so a value of each pixel of the simulated image should be recalculated:

\[ r_{mn} = 255h_n, \quad m \in 1,...,M; \]
\[ n \in 1,...,N; \quad h_n \in [0,1]. \quad (26) \]

In this way a primary image \( Foto_1 \) of the aerial photograph model is created. It represents high frequency objects on a photograph.

For low and mid frequency objects representation the same principle can be used, but here a size of the flat objects should be generated as well. After this step we have another representation of a photograph \( Foto_2 \). Using these two components a model of an aerial photograph (Fig. 6) can be created according to equation:

\[ Foto = 0.3Foto_1 + 0.7Foto_2. \quad (27) \]

Here the coefficients are chosen considering the ratio of amplitudes in real aerial photographs.

The histogram of the photograph model has a gauss shape but the investigation process showed that the most part of the aerial photographs has two-hump histograms, i.e. the relatively low quantity of mean intensity pixels.

![Figure 5. The defined hot spot model creation](image)

![Figure 6. The model of an aerial photograph \( a \) and it's histogram \( b \)](image)

![Figure 7. The final model of an aerial photograph with the hot spot distortion \( a \) and it's histogram \( b \)](image)
To simulate this feature a parabolic correction of the histogram was introduced:

\[
\begin{align*}
    r_n &= 255h_n, \\
    r_p &= \begin{cases} 
        r_n, & r_n \in [80,160], \\
        r_n, & r_n \in [80,160], \ h_n2 < \lambda; 
    \end{cases} \\
\end{align*}
\]  

(28)

where \( h_n2 \) is an additionally generated random number \((h_n2 \in [0,1])\), \( \lambda \) is the probability distribution of the mean intensity pixels (Fig. 8):

\[
\lambda = 3.75 \cdot 10^{-4}(r_n - 120) + 0.4 .
\]  

(29)

![Figure 8. The probability distribution of the mean intensity pixels](image)

To obtain a model of the aerial photograph with the hot spot distortion, an image \( S \) of the hot spot is created \((26 – 28)\). A matrix (array) of the transfer coefficients \( K_S \) using this image is created and each pixel of the photograph model is recalculated according to the ratio:

\[
k_{mn}^S = \frac{\max(S)}{s_{mn}},
\]  

(30)

where \( k_{mn}^S \) and \( s_{mn} \) are pixels of the images \( K_S \) and \( S \).

Now the modeled photograph can be distorted by the defined hot spot:

\[
Foto_{HS} = K_S Foto.
\]  

(31)

The obtained experimental results were compared to the ones given in [2]. The conclusions about the aerial photograph modeling were made: the standard deviation

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
Method & \( \sigma_t \) & \( \sigma_m \) & \( \sigma_n \) & \( \bar{r}_{20} \) & \( \bar{g}_m \) & \( \gamma_n \) & \( \gamma_m \) & \( \gamma_n \) \\
\hline
Comb & 1.12 & 6.11 & 4.83 & 7.78 & 7.4 & 7.8 & 7.8 & 7.8 \\
LPF & 11.79 & 21.15 & 16.09 & 26.57 & 18.6 & 18.6 & 12.8 & 12.8 \\
\hline
\end{tabular}
\caption{Table 1}
\end{table}

Simulation of aerial photographs allows us to investigate different features of the filtering methods, which could not be examined using just real aerial photographs. For example:

- methods operation with big amount of photographs,
- absolute and relative error values can’t be obtained while exact position of the distortion is unknown,
- divergence of errors of different algorithms.

Using the aerial photographs simulation experimental accuracy evaluation of the described methods was investigated.

### 3.2. Experimental accuracy evaluation

To compare results obtained using real photographs and simulated ones, eight models with the defined hot spot distortion were generated. Additionally to the standard deviations (20) and the standard deviation vector modules (21) the absolute and the relative error values were calculated:

\[
\delta = |a' - a|, 
\]  

(32)

\[
\gamma_n = \frac{\delta}{a} \times 100\% ;
\]  

(33)

where \( a \) is the correct value of the measured parameter, \( a' \) is the obtained value during measurement process. Mean values of the absolute and relative errors were calculated (\( \delta \) and \( \gamma_n \)). The experimental results for the histogram parceling (HP), the combined (Comb) and the low-pass filtering (LPF) methods are shown in Table 1.
values for the real aerial photographs and for the simulated ones are very similar. This shows that the models for the aerial photograph simulation are created properly.

The experimentally obtained absolute and the relative errors have the same values (Table 1) because the hot spot distortion center coordinates were chosen equal to 100 \( C_{HS}(100,100) \). According to (33) the values should be equal.

For the images averaging method evaluation and the quantity of the used images influence to the calculation accuracy investigation, fifty models of aerial photographs were generated. The graphs of the obtained results are shown in Fig. 9 and in Fig. 10.

There we see optional trends of the calculation errors: using bigger amount of images lower error values can be obtained.

The results show as that the distortion position error given by the combined method converges faster to zero value than the position error given by the general images averaging method without HP application. For instance: the error value of 2% could be obtained using just 14 images when the combined method is applied, while the general images averaging method requires 24 images at least. That means the same results we can obtain by processing just about 60 percent of the previous images.

**Conclusions**

1. For the investigated methods accuracy evaluation the creation of the aerial photograph models is proposed.
2. The described methods accuracy is evaluated and compared.
3. By applying the Histogram parceling method, quantity of images used for the distortion model creation can be reduced about 40÷50% to compare with Images averaging method.
4. It is found that the described in [2] Histogram parceling method in combination with the Images summing method (combined method) gives the best results comparing accuracy and resources needed for calculations.

**References**


RADIOMETRINIO IDKRAIPYMO FILTRAVIMO METODO TIKSLUMO ÁVERTINIMAS

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Santrauka

Straipsnyje apþvelgiamos problemos kylanèios dël karðtosios dëmës (hot spot) efekto sutinkamo aerofotografijoje. Apraðyti tokio tipo õdkraipymams filtruoti skirti metodai (vaizdo vidurkinimo, ëemo daþ nio filtravimo, histogramos skaidymo, kombinuotasis).


Apraðyti eksperimentø metu gauti rezultatai pritaikius minètus metodus. Padarytos iðvados apie nagrinëtø metodø efektyvum¹.

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