Color Rendering Correctness Estimation of Aerial and Satellite Images and Restoration of Color Balance

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ABSTRACT:

Despite the fact that with a certain degree of generalization our idea of object's color around us can be considered the same, the problem of estimation of the color rendering correctness is very relevant for image's radiometric correction. The color rendering correctness is one of the most important indicators of aerial and space images visual (photographic) quality, since it determines the quality of objects brightness features transmission by the image. In aerial and space imaging for phototopographic surveying (Bianco et al, 2015), to date, neither an indicator of color imbalance nor a method for its estimation has been developed, therefore it is not possible to assess objectively the presence and degree of color imbalance. A method for quantitative estimating the color imbalance of an image suggested in paper. The criterion for evaluating the image's color imbalance, a method for it's determining and experimental verification of the developed method by correcting the image's color balance are shown.

1. INTRODUCTION

Color rendering in photography is the correctness of object's color reproducing when photographing. Color rendering considered correct if there are no color distortions in image compared to object's color. Among the main factors of color distortion are the following:

– incorrect spectral photosensitivity characteristic of matrix color channels (pixels with different light filters – blue, green or red);
– gradation process irregularity – difference in color channels contrast degree in image.

In practice, image's color reproduction can be considered correct if the photographed scale of achromatic tones is transmitted over the entire length by gray photographic darkening without noticeable color shades (Lapauri and Sheberstov, 1956).

A color rendering correctness indicator of a digital image is it's color balance. The image's color balance expresses the correspondence (balance) of three color-separated images gradation characteristics.

The color balance characterizes the color-separated pixel values correspondence of gray field in color image. Color image parts considered balanced if color components values of gray objects are equal. Difference in color-separated pixel values could be a quantitative characteristic of color imbalance (Iofis E.A., 1981).

Despite the color correction problem urgency, including aerial and space imagery, to date, neither color imbalance indicator nor it's evaluating method has been developed. For this reason it is not possible to assess objectively the presence and degree of color imbalance.

The aim of the study was to develop a method for quantitative estimating the color imbalance of an image.

2. METHODOLOGY

To develop a method for quantitative estimating the color imbalance of an image it is necessary to solve the following tasks:

1. to develop a criterion for evaluating the image's color imbalance and a method for it's determining;
2. experimental verification of the developed method by correcting the image's color balance.

2.1 Development a criterion for evaluating the image's color imbalance and method for it's determining

According to image color balance definition, the quantitative characteristic of imbalance is the difference in achromatic objects image color components. Achromatic objects can be white, gray, or black. The problem is that aerial and space images do not always contain such objects to evaluate the balance of three color components. The algorithm for image color imbalance determining in automatic mode should solve the following tasks:

1. search for pixels belonging to images of achromatic objects;
2. evaluate the value of color imbalance based on the selected pixels;
3. a control procedure for restoring the color balance of an image based on the results of color imbalance assessment.

2.1.1 Automatic search for pixels belonging to the image of achromatic objects

In case of ideal achromatic object color reproduction by image, red R, green G and blue B color components of object's pixels are equal to each other, i.e., speaking of an additive color model, R = G = B. Therefore, the task of searching for gray pixels in image is to identify pixels with the closest values of red, green and blue components – achromatic pixels. For each pixel, the value of its brightness is calculated as a vector length in RGB

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color space $\vec{P}$ (Dzhadd and Vyshetski, 1978):

$$|\vec{P}| = \sqrt{{R_P}^2 + {G_P}^2 + {B_P}^2} \quad (1)$$

where R_P, G_P and B_P = values of red, green and blue components of pixel color – vector $\vec{P}$ coordinates in RGB color space respectively

An achromatic pixel that has equal brightness with a color pixel characterized by vector $\vec{P}$ can also be represented by vector $\overrightarrow{GRAY_P}$ in RGB color space, besides the $\overrightarrow{GRAY_P}$ length is equal to $\vec{P}$ (Figure 1).

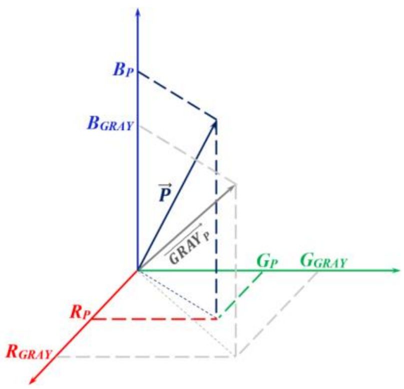

Figure 1. Vector $\vec{P}$, characterizing image pixel color and vector $\overrightarrow{GRAY_P}$, have the same length as $\vec{P}$ and characterizing the panchromatic pixel color in RGB color space.

The gray vector color components are equal to each other and calculated as:

$$R_{GRAY} = G_{GRAY} = B_{GRAY} = \frac{|\overrightarrow{GRAY_P}|}{\sqrt{3}} = \frac{\sqrt{{R_P}^2 + {G_P}^2 + {B_P}^2}}{\sqrt{3}} \quad (2)$$

where R_{GRAY}, G_{GRAY} and B_{GRAY} = values of red, green and blue components of gray pixel color – vector $\overrightarrow{GRAY_P}$ coordinates in RGB color space respectively

Analyzing the difference between pixel color components values R_P, G_P and B_P and values of gray pixel color components R_{GRAY}, G_{GRAY} and B_{GRAY} the pixel color proximity degree to gray is estimated. The evaluation criterion can be the δ value, determined as:

$$\delta = |R_P - R_{GRAY}| + |G_P - G_{GRAY}| + |B_P - B_{GRAY}| \quad (3)$$

Obviously, the lower δ value of pixel, the closer its color to achromatic (gray).
The image color imbalance presents in pixels of each digit. In case of 8 bits/pixel image radiometric resolution, the number of digits is 256 (pixel values from 0 to 255). Therefore, the task of image achromatic pixels searching is to find pixels in each digit that have the lowest sum of color components deviations from gray δ. To do this, all image pixels must be sorted by bit numbers. The pixels bit number K is determined by color component value of gray pixel, that have the equal brightness, i.e.:

$$K = R_{GRAY} = G_{GRAY} = B_{GRAY} \quad (4)$$

For each bit number K, an array of color components deviations from gray sums δ_K is formed. In case of 8 bits/pixel radiometric resolution image, 256 arrays are formed. Within each array δ_K, the elements are sorted in ascending (or descending, in this case it doesn't matter) order and a specified percentage of minimum values is taken. The minimum values percentage can be specified by user. Experimentally established that 10% is optimal, so this value will be used in further calculations. The extreme (largest) value of δ_K, included in given percentage of minimum values, is designated as δ_{Kmin}. It will be a criterion when selecting pixels for color imbalance estimating. Pixels for which the δ_K value does not exceed a certain minimum δ_{Kmin} can be considered gray for a given bit number K. These pixels can be used to determine the color imbalance value.

2.1.2 Color imbalance estimation

Pixels i in each bit number K, for which the sum of deviations from gray for each color component δ_{Ki} does not exceed a certain value δ_{Kmin}, are selected throughout the image:

$$\delta_{Ki} \leq \delta_{Kmin} \quad (5)$$

For selected pixels, the average color deviation from gray of achromatic object image is determined for each color component.

$$\delta R_K = \frac{\sum_{i=1}^{n_K}(R_{Ki} - K)}{n_K};\ \delta G_K = \frac{\sum_{i=1}^{n_K}(G_{Ki} - K)}{n_K};\ \delta B_K = \frac{\sum_{i=1}^{n_K}(B_{Ki} - K)}{n_K}, \quad (6)$$

where n_K = number of pixels in each bit number K, satisfying condition (5)

The result of (6) are three one-dimensional arrays of average deviations from gray for three color components δR, δG, δB. The array's length is equal to number of digits K, for radiometric resolution of 8 bits/pixel image it is 256.
Figure 2 shows graphical representation of average deviations from gray for three color components δR, δG, δB for achromatic object in each pixel bit number K in aerial image.

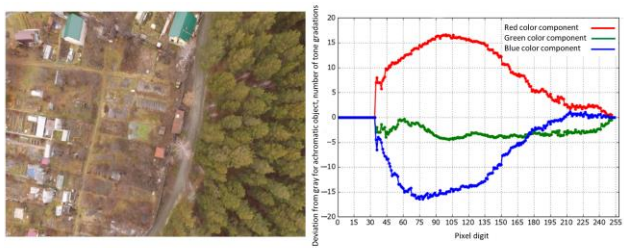

Figure 2. Average deviations from gray for three color components δR, δG, δB for achromatic object in each pixel bit number K (pixel digit).

The value of overall color imbalance for each color component is determined by figure's area, formed by deviation from gray for color components δR, δG, δB for achromatic object graph and the abscissa axis. It is convenient to present the graph itself as a bar chart, since it displays a set of discrete gray values and their corresponding deviations from gray values for color components. Figure 4 shows the bar chart of deviation from gray, based on red color component for aerial image, shown in Figure 2.
We can see that the area of figure SR, formed by the bar chart in Figure 3 with the abscissa axis, is equal to sum of products of each column height – the deviation from gray value for red component in digit – by its base dK – one digit number.

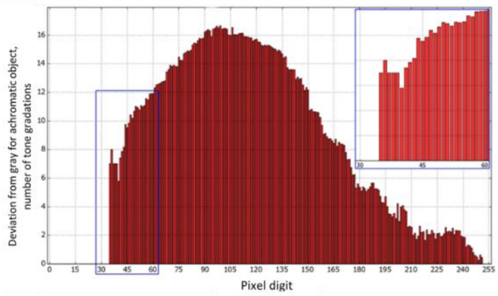

Figure 3. The bar chart of deviation from gray, based on red color component for aerial image.

The areas of figures *SG* and *SB*, formed by abscissa axis and bar charts of deviations from gray for green and blue components, respectively, are determined in a similar way:

$$SR = \sum SR_K = \sum |\delta R_K| \cdot dK = \sum |\delta R_K|;$$
$$SG = \sum SG_K = \sum |\delta G_K| \cdot dK = \sum |\delta G_K|; \quad (7)$$
$$SB = \sum SB_K = \sum |\delta B_K| \cdot dK = \sum |\delta B_K|,$$

where $|\delta R_K|$, $|\delta G_K|$ and $|\delta B_K|$ = respectively, the modules of deviations from gray for red, green and blue color components of an achromatic object in the *K*-bit number

Dividing the figures *SR*, *SG* and *SB* area values by total number of digits *K* (N_K), we obtain the average deviation from gray of an achromatic for each color component:

$$\Delta R = \frac{\sum_{K=0}^{N_K} |\delta R_K|}{N_K} = \frac{SR}{N_K};$$
$$\Delta G = \frac{\sum_{K=0}^{N_K} |\delta G_K|}{N_K} = \frac{SG}{N_K}; \quad (8)$$
$$\Delta B = \frac{\sum_{K=0}^{N_K} |\delta B_K|}{N_K} = \frac{SB}{N_K},$$

From (7) and (8) it follows that the average deviation from gray value of an achromatic object for each color component over all bit numbers can be used as an indicator of color imbalance, since it is proportional to area, occupied by the bar chart.
The general characteristic of color imbalance across the three color components is the length of vector $\vec{\Delta}$ in RGB color space (Figure 4), which is calculated as:

$$|\vec{\Delta}| = \Delta = \sqrt{\Delta R^2 + \Delta G^2 + \Delta B^2} \quad (9)$$

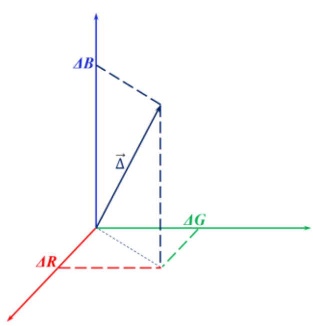

Figure 4. Vector $\vec{\Delta}$ shows the image's color imbalance value and direction.

2.2 Experimental verification of method for color imbalance determining by restoring the image color balance

The control procedure for image color balance restoring is performed to verify the reliability and correctness of the proposed method for color imbalance determining. The task of restoring the color balance is to compensate deviations from gray by introducing appropriate corrections in pixels color components values, corresponding to their bit numbers *K*.
A feature of color balance violation, generally, is the smooth function kind over entire range of pixel brightness gradations. Figure 5 shows an example of artificial color balance disturbance in red color component using a Fujifilm Test Image in a graphic editor using the curves tool.

Figure 5. Artificial color balance disturbance in red color component using a Fujifilm Test Image.

Reliability of average deviation from gray estimating of an achromatic object δR_K, δG_K, δB_K for *K*-bit number pixels strongly depends on statistical sample representativeness – the larger it is, the more reliable the result will be. The pixels number distribution in digital image depending on *K*-bit number is non-uniform, i.e. an image contains an unequal number of different brightness pixels. As a result, the smoothness of color imbalance curve is disrupted and the actual evaluation graph looks like the one shown in Figure 6.

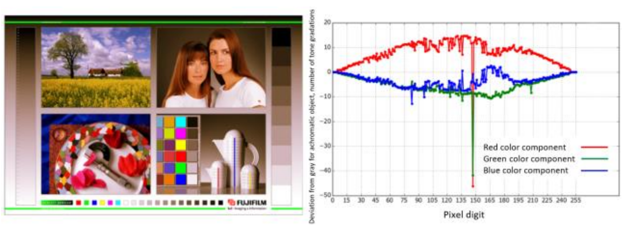

Figure 6. Graphs of color components imbalance for Fujifilm Test Image with characteristic spikes arising from the non-uniform pixels distribution across digits.

Restoring color balance involves introducing corrections that are numerically equal to deviations from gray δR_K, δG_K, δB_K into corresponding *K*-bit number pixel values with an opposite sign.

$$\begin{vmatrix} R'_{K\ i,j} \\ G'_{K\ i,j} \\ B'_{K\ i,j} \end{vmatrix} = \begin{vmatrix} R_{K\ i,j} \\ G_{K\ i,j} \\ B_{K\ i,j} \end{vmatrix} + \begin{vmatrix} -\delta R_K \\ -\delta G_K \\ -\delta B_K \end{vmatrix} \tag{10}$$

where $R'_{K\ i,j}$, $G'_{K\ i,j}$, $B'_{K\ i,j}$ = i,j pixel’s color components of with restored color balance
$R_{K\ i,j}$, $G_{K\ i,j}$, $B_{K\ i,j}$ = original i,j pixel’s color components
i,j = row and column number of the image respectively

Due to lack of certain digit statistical sample representativeness, outliers appear, as shown in Figure 7. Restoring the color balance according to (10) in these digits leads to image’s defects as color artifacts (Figure 7).

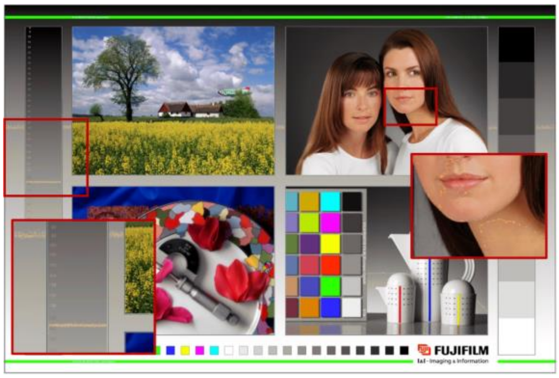

Figure 7. Color artifacts as a result of color balance restoration using statistically unrepresentative samples of some pixel digits.

In order to restore the color balance correctly, it is necessary to filter outliers and smooth out graphs of average deviations from gray of achromatic object color components δR_K, δG_K, δB_K.
To solve the problem of sample representativeness while estimating δR_K, δG_K, δB_K allows calculating these values not for each pixel digit separately, but averaging over a certain range of digits, for example, by dividing the entire range of digits K by 4, 8, 16 or another number of equal intervals. Experimentally shown that for a 8-bit image, the most optimal is dividing the range of 256 bits into 32 intervals, i.e. 8 bits in each interval. Figure 8 shows an example of Fuji Test Image average color imbalance estimation over 32 pixel digit intervals.

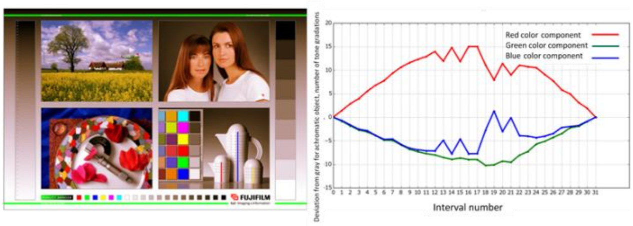

Figure 8. Graphs of Fuji Test Image average color imbalance estimation over 32 pixel digit intervals.

Shown in Figure 8 graphs have a more smoothed appearance than graphs obtained for each bit number pixel category (Figure 6), but they also have local maxima and minima. δR_K, δG_K and δB_K averaging at on 32 intervals avoids the appearance of color artifacts when restoring color balance, however, it was not possible fully to perform a restoration using the received corrections (Figure 9). Figure 9 shows that the fields of the gray wedge and gray scale at a certain brightness are not perfectly gray, but have a visually noticeable color shade. This is typical for pixels in those intervals that have outliers on the color imbalance graph in Figure 6.

Figure 9. The result of color balance restoration based on averaged correction values at 32 pixel bit intervals.

The smoothing procedure helps to avoid the occurrence of local extremes on color imbalance graphs. Experimental testing of various smoothing filters has shown that the most stable and reliable result can be obtained using the moving average method. (Kiryanov and Kiryanova E.N., 2006;) The optimal width of smoothing filter was 9 values, i.e. the smoothed value of deviation from gray for achromatic object color components on a pixel digits interval $I \in [0; 31]$ – $\delta R'_I$, $\delta G'_I$, $\delta B'_I$ is determined by the average value of 9 neighboring δR_I, δG_I, δB_I. When using this filter, uncertainty of the edge values arises, i.e. when the filter kernel is in the interval values $I = 0, 1, 2, 3$ and $I = 28, 29, 30, 31$. In this case, unsmoothed values are used.

$$\begin{cases} \begin{vmatrix} \delta R'_I \\ \delta G'_I \\ \delta B'_I \end{vmatrix} = \frac{1}{9} \cdot \begin{vmatrix} \sum_{k=0}^{4} \delta R_{I\pm k} \\ \sum_{k=0}^{4} \delta G_{I\pm k} \\ \sum_{k=0}^{4} \delta B_{I\pm k} \end{vmatrix} \ if\ I \in [4; 27], \\ \begin{vmatrix} \delta R'_I \\ \delta G'_I \\ \delta B'_I \end{vmatrix} = \begin{vmatrix} \delta R_I \\ \delta G_I \\ \delta B_I \end{vmatrix} if\ I \in [0; 3] \vee [28; 31]. \end{cases} \tag{11}$$

Figure 10 shows the graphs of smoothed deviations from gray of the color components $\delta R'$, $\delta G'$, $\delta B'$ and the Fuji Test Image.

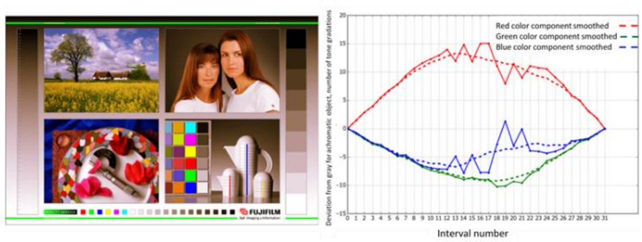

Figure 10. Graphs of Fuji Test Image average color imbalance estimation over 32 pixel digit intervals, obtained with smoothing filter (11).

Figure 11 shows the Fuji Test Image, obtained by restoring the color balance using smoothed correction values.

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Figure 11. The result of color balance restoring based on smoothed averaged correction values.

There is no visually noticeable color balance disturbance in Figure 11, that allows us to conclude that the proposed method for color imbalance estimation, using averaging and smoothing methods, works correct. Table 1 shows the results of Fuji Test Image color imbalance estimation with a disturbed color balance (Figure 5, 6, 8) and with a restored color balance (Figure 11).

Average deviation from gray of an achromatic object by color components, number of tone gradations					
Figure 5, 6, 8			Figure 12		
Red ΔR	Green ΔG	Blue ΔB	Red ΔR	Green ΔG	Blue ΔB
8.9	-5.6	-4.4	1.0	-0.4	-0.9
Total color imbalance Δ					
11.4			1.3		

Table 1. Color imbalance estimation results of Fuji Test Image with distorted color balance and with restored color balance.

The results obtained in Table 1 are fully consistent with the visual perception of image’s color balance. It allows us to conclude, that the developed color imbalance criterion *Δ* is representative, the proposed method for determining it is appropriate, so it is possible to use it to estimate the images quality in terms of color correctness.

2.3 Comparison the developed method of color balance correction with existing alternative methods

There are different ways to restore color balance in digital image processing. The most well-known and widely used are the «Gray world», the simplest color balance (Limare et al, 2011), the robust automatic white balance algorithm (Huo et al, 2006), the sensor correlation method (Tominaga et al, 2002; Tominaga and Brian, 2002), chromatic adaptation methods (Lindbloom, 2017; Bianco and Schettini, 2010), D65 white point (desired reference light source) (Technical Bulletin TB-2018-001, 2018). These methods are widely described in literature and implemented in specialized software, designed for image processing – from open source libraries such as OpenCV, specialized Python libraries, Matlab, etc. to graphic editors such as Adobe Photoshop, GIMP, Corel Draw, Capture One, etc.
The next step in verifying the proposed method of color imbalance estimation (let's call it the «Gray Pixel method») is to compare the results of restoring color balance with the results, obtained by the mentioned alternative methods.
For these purposes, several images of different subject orientation were selected, these images is shown in Figure 12.

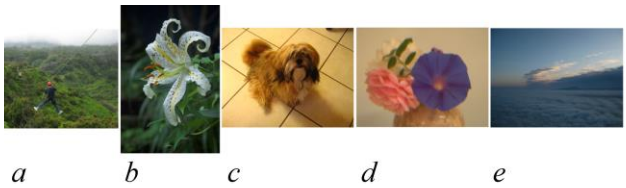

Figure 12. Sample of images to compare the color balance restoration algorithms: *a – Image1*, *b – Image2*, *c – Image3*, *d – Image4*, *e – Image5*.

Table 2 shows the color imbalance estimation results of the original images and images obtained after restoring the color balance using the developed «Gray Pixel method» and alternative methods.

Image	Color balance restoration method	Color imbalance, number of tone gradations			
		Red *R*	Green *G*	Blue *B*	Total *Δ*
Image 1	Original image	-1,63	1,89	-0,39	2,52
	«Gray Pixel method»	-0,57	0,54	-0,03	0,79
	«Gray world»	-3,2	-3,11	5,79	7,31
	The simplest color balance	-1,35	0,59	0,67	1,62
	The robust automatic white balance algorithm	-0,83	-1,23	1,93	2,44
	The sensor correlation method	-9,37	-2,24	10,16	14,01
Image 2	Original image	-3,12	3,1	-0,27	4,41
	«Gray Pixel method»	-1,21	1,28	-0,18	1,77
	«Gray world»	-1,34	0,31	0,84	1,61
	The simplest color balance	-1,19	1,49	-0,46	1,96
	The robust automatic white balance algorithm	0,72	-1,68	0,83	2,01
	The sensor correlation method	-5,81	3,49	1,8	7,01
Image 3	Original image	25,56	-0,89	-35,25	43,55
	«Gray Pixel method»	2,07	0,1	-2,35	3,13
	«Gray world»	14,34	-11,55	-5,2	19,13
	The simplest color balance	15,3	-6,06	-11,85	20,28
	The robust automatic white balance algorithm	3,66	-2,55	-1,98	4,88
	The sensor correlation method	7,86	-9,88	0,62	12,64
Image 4	Original image	8,22	-2,68	-8,02	11,79
	«Gray Pixel method»	1,92	-0,97	-1,72	2,76
	«Gray world»	10,22	-9,73	-4,35	14,77
	The simplest color balance	3	3,21	-8,94	9,96
	The robust automatic white balance algorithm	1,16	0	-1,76	2,11
	The sensor correlation method	10,57	-12,41	-1,84	16,41
Image 5	Original image	-2,81	0,32	1,8	3,35
	«Gray Pixel method»	-0,9	0,06	0,66	1,11
	«Gray world»	-1,21	4,12	-3,72	5,68
	The simplest color balance	-2,71	1,81	0,31	3,27
	The robust automatic white balance algorithm	5,16	-0,82	-5,22	7,38
	The sensor correlation method	-5,54	-4,4	8,14	10,79

Table 2. Color imbalance estimation results of images in Figure 13 and images obtained after color balance restoration using the «Gray Pixel method» and alternative methods.

The results in Table 2 show that images obtained by restoring color balance using the «Gray Pixel method» have the smallest overall color imbalance in three out of five cases. The exceptions are *Image2* and *Image4*, for which the proposed method showed the second lowest result. This allows us to conclude that the «Gray Pixel method» is superior to alternative methods. The numerical estimate given in Table 2 is in complete agreement with the visual one (Figures 13).

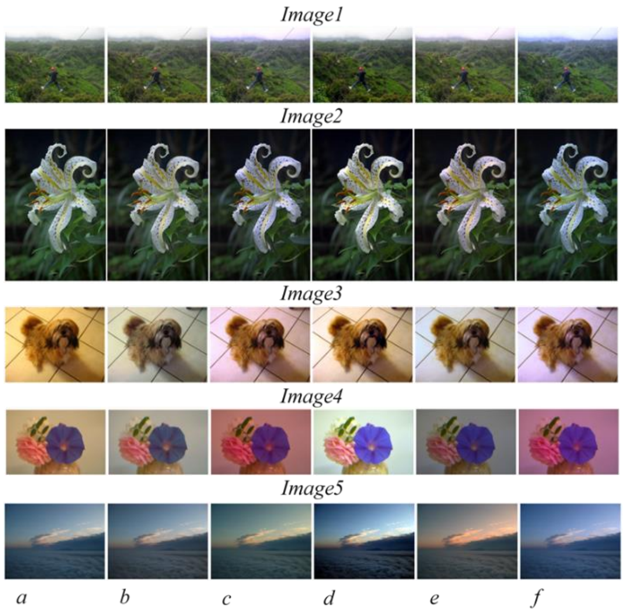

Figure 13. Original image and results of it’s color balance restoring using various algorithms: *a* – the original image, *b* – the «Gray Pixel method», *c* – the «Gray world» method, *d* – the simplest color balance, *e* – the robust automatic white balance algorithm, *f* – the sensor correlation method.

Visual analysis of images in Figure 13 showed the obvious advantage of using the «Gray Pixel method» in comparison with alternative methods of restoring color balance. It consists in the fact that when processing with the proposed algorithm, there is no degradation in image quality, as is observed when using other methods considered.
Figure 14 shows an example of color balance restoring in aerial image.

Figure 14. Color balance restoring of aerial image.

3. CONCLUSION

As a result of research, a method for color rendering correctness estimation was developed and it’s criterion – color imbalance. A method for automatically determining the value of color imbalance is created. The results of experimental verification by restoring the images color balance are presented. The advantage of the developed method of color balance correction in comparison with alternative methods is practically confirmed and shown.
Application of proposed method for color balance evaluating and restoration while aerial and space imagery processing does not introduce geometric distortions into the images and allows to improve the visual quality of created topographic products.

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