Automatic White Balance Algorithms for Digital Still Cameras – a Comparative Study

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Key Words: *Automatic White Balance; Digital Photography; Color Temperature.*

Abstract. *Automatic white balance is an important function of digital still cameras. Failure to estimate illumination chromaticity correctly will result in invalid overall color cast in the final image. The goal of automatic white balancing is to estimate accurately the color of the overall scene illumination and to make the image look as if is taken under canonical light. This article discusses some of the basic white balance algorithms, making a comparison between them, and proposes a modification of one of the methods. For comparison purposes, test images are used, taken at different settings of white balance of digital still camera, various color temperatures of the scenes, and under six calibrated illumination environments.*

1. Introduction

The human visual system (HVS) has the ability to map „white" colors to the sensation of white, even though an object has different radiance when it is illuminated with different light sources. In other words, if you were shown a sheet of white paper under natural daylight or under incandescent lighting, or even under fluorescent lighting, you would say that it was white. This phenomenon is called color constancy. When an image is captured by a digital camera, the sensor response at each pixel depends on the illumination. That is, each pixel value recorded by the sensor is related to the color temperature of the light source. When a white object is illuminated with low color temperature light, it will appear reddish in the recorded image. Similarly, it will appear bluish under a high color temperature. The purpose of white balance is to process the image so that visually it looks the same way, regardless of source of light.

There are various automatic white balance (AWB) algorithms proposed in the literature: Gray world, Retinex theory, perfect reflector, standard deviation-weighted gray world, and etc. [2-6,9]. Most of these algorithms make certain assumptions of the color distribution of the image. They differ in the way the illumination is estimated.

The aim of this paper is to quantify the effects of white-balancing errors in digital photography for different AWB algorithms. This is achieved by means of subjective and non-subjective tests. Different natural and studio images are utilized in order to study the effect of image contents on the acceptability of white point shifts.

The structure of this paper is as follows: color capture in digital photography is briefly examined in Section II. Section III contains short descriptions of the explored AWB algorithms. Experimental setup and obtained results are reported in Section IV. Some concluding remarks are made in Section V.

2. Digital Photography – Color Capture

A digital image color is formed by the intensity values of the red, green and blue channels. Each of these values is influenced by three physical characteristics: (*i*) source of light (also called illuminant), (*ii*) object reflectance or transmittance, (*iii*) sensor spectral response (combination of spectral characteristics of colorants used in the Bayer filter [1] and spectral sensitivity of the photodetectors - CCD or CMOS).

2.1. Sources of Light

To have an image, it is necessary to have a light source (illuminant). Normalized distribution of light at different wavelengths gives spectral power distribution of the illumination as a function of wavelengths. The graph of the power emittance over the visual spectrum is called relative spectral power distribution curve for this specific illuminant or source. *Figure 1* shows the spectral power distribution of three common light sources: (a) typical daylight, which is continuous over the visible spectrum; (b) tungsten light (also very smooth); (c) fluorescent lamp, which has sharp spikes in the spectrum power distribution.

2.2. Object Reflectance/Transmittance

When electromagnetic waves from a light source reach an object, part of them is absorbed and depending on the object, the other part is reflected or transmitted. Regardless by the source of light or the individual perception, an object always absorbs, reflects or transmits the same percent of each wavelength of the spectrum. That is why the spectral reflectance (transmittance) of an object, can be represented as a function of the wavelength. The spectral reflectance corresponding to two typical object colors is shown in *figures 2(a)* and *figures 2 (b)*. The red object on *figures 2(a)* absorbs almost all of the low frequency components (blue to green) and reflects almost all high frequency wavelengths. The amount of reflected low frequency components is very small and therefore the visible color is bright red.

The gray object (*figure 2 (b)*) has approximately constant value of spectral reflectance for the different wavelengths, which results in a light gray color (as the curve is raised up).

Illumination and object reflectance (or transmittance) together determine what is known as *color stimulus*.

2.3. Sensor's Spectral Response

Almost all sensors used in digital cameras (except Foveon) are sensitive only to the intensity of light and not to its components (different wavelengths). That is why having a color image requires color filters, most often an RGB Bayer filter. Different filter elements have different spectral transmittance depending on the colorants used. The sensors themselves have different sensitivity and even for the same manufacturer [1] they have differences in the spectral characteristics (*figure 3*).

Digital cameras need to „adapt" not only to the different color stimulus, but to the spectral response of the different sensors and these define the need for and the challenges in front of the automatic white balance algorithms in digital photography.

3. Explored Algorithms – A Breif Description

3.1. Gray World Theory

One of the simplest and the most often used assumptions about the color constancy is the so-called Gray World Theory (*GWT*): the majority of all visual scenes in the world can be integrated to the gray, i.e. $R_{avg} = G_{avg} = B_{avg}$. The most direct solution for automatic correction of the white is to calculate the mean values for each color channel of the captured image ($R_{avg}, G_{avg}, B_{avg}$) and to use them to calculate the ratios between them as the green channel's average is most often used for a base: $corrR = R_{avg} / G_{avg}$ and $corrB = B_{avg} / G_{avg}$. The obtained coefficients are used to correct the color values of the pixels in the image.

3.2. Retinex Theory/ Perfect Reflector Method

Another possible method for white balance is based on the assumption that a sample of white color is associated with the maximum cone response of the human visual system [2] and should provoke maximum signal in the camera for all the three color channels - that is the so-called Retinex Method (*RM*) or Perfect Reflector Method (this method can be regarded as a special limiting case of Retinex). It locates the brightest pixel $R_{\max}$, $G_{\max}$ and $B_{\max}$, and assigns it as a reference white point.

If R, G and B are respectively the red, green and blue channels in the image, the white balancing may be obtained through $R/R_{\max}$, $G/G_{\max}$ and $B/B_{\max}$ for each pixel of the image. Another method to determine the correction coefficients is calculated by Eq. (1), where the green channel stays unchanged:

$$(1) \quad corrR = \frac{G_{\max}}{R_{\max}}, \quad corrB = \frac{G_{\max}}{B_{\max}}, \quad corrG = 1 .$$

3.3. Gray World + Retinex Theory

This method (*GWR*), proposed by Edmund Lam [3], is a combination from the upper two methods - the Gray world assumption and the Retinex theory. The idea is to find correction coefficients which will satisfy both methods. Again, the green channel stays unchanged and the correction coefficients for the red and blue channels are calculated from Eq. (2):

$$(2) \quad \begin{bmatrix} \sum\sum I_R^{\,2} & \sum\sum I_R \\ \max I_R^{\,2} & \max I_R \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} \sum\sum I_G \\ \max I_G \end{bmatrix} \quad \text{and}$$

$$\begin{bmatrix} \sum\sum I_B^{\,2} & \sum\sum I_B \\ \max I_B^{\,2} & \max I_B \end{bmatrix} \begin{bmatrix} c \\ d \end{bmatrix} = \begin{bmatrix} \sum\sum I_G \\ \max I_G \end{bmatrix}$$

where I_R, I_G and I_B are the RGB values of the original image, a and b are the correction coefficients for the red channel, and c and d for the blue channel.

3.4. Standard Deviation-weighted Gray World

The standard deviation-weighted gray world (*SDWGW*) algorithm extends the Gray world assumption and is proposed by Lam et al. [4]. It subdivides the image into p blocks and for each one of them calculates standard deviations (σ_R, σ_G, σ_B) and means (μ_R, μ_G, μ_B) of the R, G, and B channels (in this paper the number of blocks p is 12, as the used Olympus camera has a frame format 4/3). After that, the mean values for each channel are calculated using the weight coefficients of the blocks. For example, for the k-th block weighted average standard deviation for green channel can be calculated according Eq. (3)

$$(3) \quad StdAvgG = \sum_{k=1}^{p} \frac{\sigma_G(k)}{\sum_{i=1}^{p} \sigma_G(i)} * \mu_G(k) .$$

Based on these values for each channel, the correction coefficient for green channel is calculated as it is shown in Eq. (4)

$$(4) \quad corrG = \frac{StdAvgR + StdAvgG + StdAvgB}{3 * StdAvgG} .$$

According the green channel, the correction coefficients for blue and red channels are calculated as it is shown in Eq. (5)

$$(5) \quad corrR = \frac{StdAvgR + StdAvgG + StdAvgB}{3 * StdAvgR} ,$$

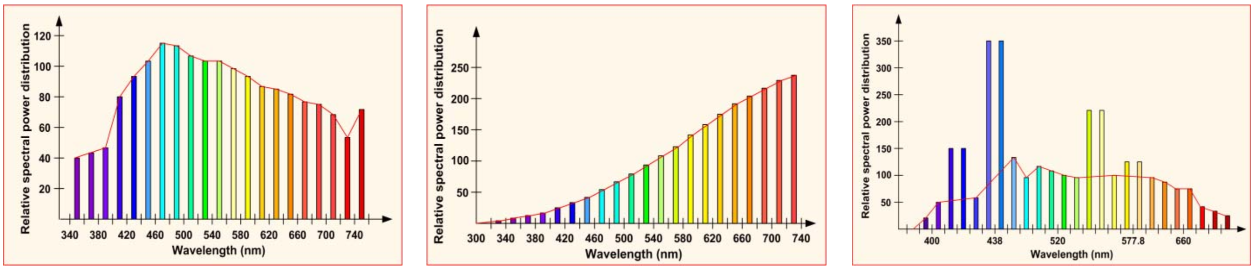
$$corrB = \frac{StdAvgR + StdAvgG + StdAvgB}{3 * StdAvgB} .$$

3.5. Standard Deviation and Luminance-weighted Gray World

The standard deviation and luminance-weighted gray world algorithm (*SDLWGW$_1$*) is also proposed by Lam et al. [5] and it is a variation of the *SDWGW* algorithm. The image is similarly subdivided, but the weights are defined as follows - Eq. (6) (green channel, for example):

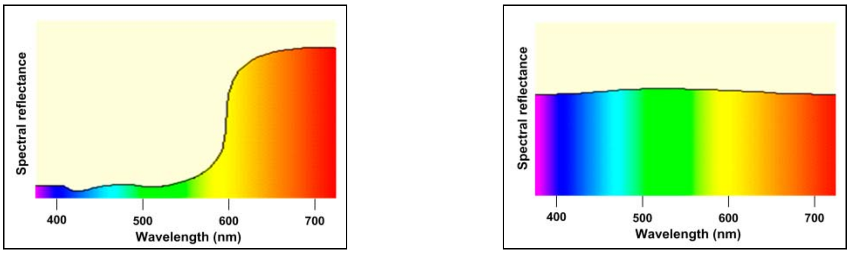
$$(6) \quad \mu\_lum\_g(k) = \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{L\_w_k(i,j)}{\sum_{x=1}^{m} \sum_{y=1}^{n} L\_w_k(x,y)} * G_{i,j}(k)$$

where m and n are the sizes of the block, $L\_w_k(i,j)$ is the value of the luminance of the pixel in row i and column j of block



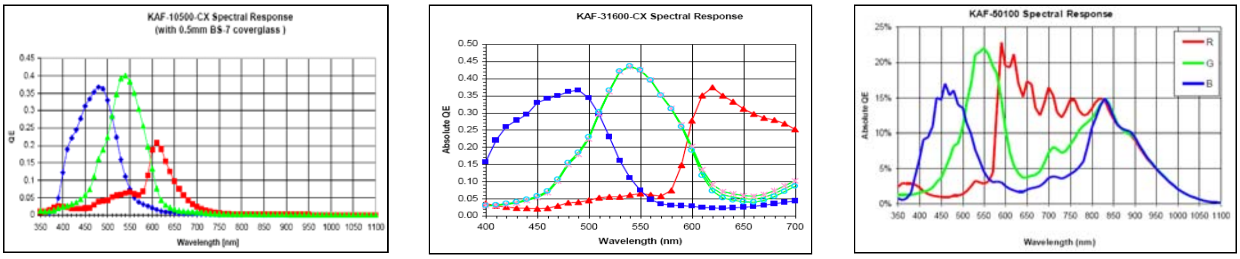
(a) Daylight (b) Incandescent light (c) Fluorescent light

Figure 1. Spectral power distribution of different sources of light



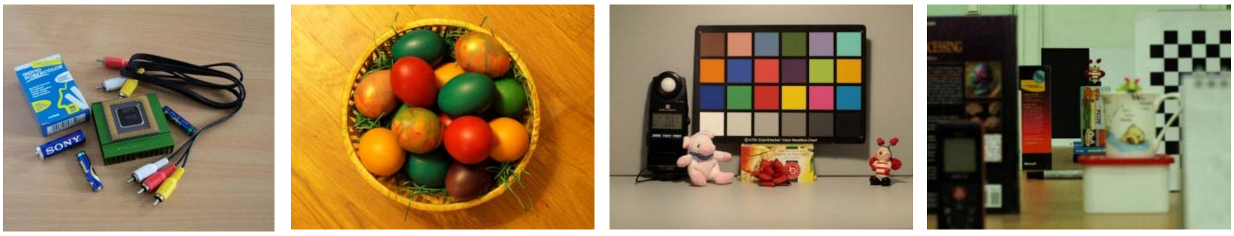
(a) Vivid red object (b) Light gray object

Figure 2. Spectral reflectance of different color objects



(a) Kodak KAF-10500-CX (b) Kodak KAF-31600-CX (c) Kodak KAF-50100

Figure 3. Spectral response of different types Kodak CCD sensors



(a) Room scene (shade) (b) Energy saving lamp (c) Macbeth chart (d) Fluorescent light

Figure 4. Some test images illuminated by different light sources

(a) Tungsten light (b) Gray world (c) SDWGW$_2$ (d) YCbCr color space

Figure 5. Results after AWB for image illuminated by tungsten light

(a) Fluorescent ligh (b) Gray world (c) $SDWGW_{1,2}$ (d) YCbCr color space

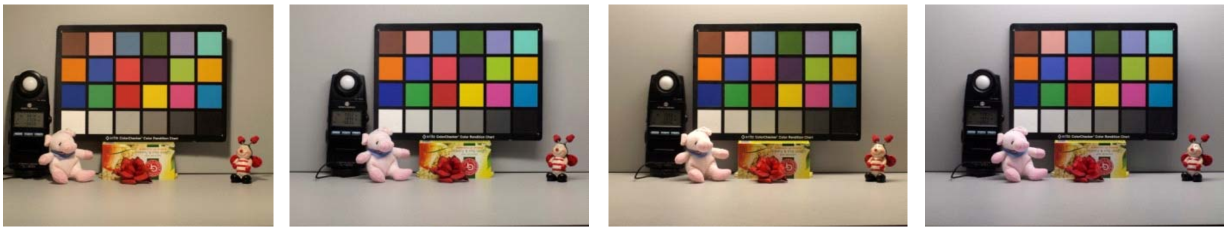
Figure 6. Results after AWB for image illuminated by fluorescent light

(a) Gray world (b) Retinex and GWT (c) Retinex (d) YCbCr color space

Figure 7. Results after AWB for image illuminated by energy saving lamp

(a) Shade in room (b) Retinex and GWT (c) Retinex (d) YCbCr color space

Figure 8. Results after AWB for image in shade



(a) Illuminant A (b) TL84 (c) U30 (d) D50

Figure 9. Some of the original images of Macbeth card taken under different standard illuminants

number k, $G_{i,j}(k)$ is the value of the green component of the pixel in row and column of block number k. The calculated weights for each of the p blocks form the weighted luminance deviation $StdLum$ for each channel, for example the green channel - Eq. (7)

$$StdLumG = \sum_{k=1}^{p} \frac{\sigma_G(k)}{\sum_{i=1}^{p} \sigma_G(i)} * \mu\_lum\_g(k) \,. \tag{7}$$

Based on the calculated values for each channel, the correction coefficients are calculated as shown in Eq. (8) for green channel and similarly for the red and blue channels (in according to Eq. (5))

$$corrG = \frac{StdLumR + StdLumG + StdLumB}{3 * StdLumG} \,. \tag{8}$$

As an improvement (*SDLWGW*$_2$) of this method the authors propose the correction of the channels to be calculated in accordance to the gray world theory – Eq. (9)

$$corrR' = \frac{corrR}{corrG} ,\ corrB' = \frac{corrB}{corrG} ,\ corrG' = 1 \,. \tag{9}$$

3.6. Adjacent Channels Adjustment by Standard Deviation and Luminance

In this algorithm (*SDL*), proposed again by Lam et al. [6] the new correction values are computed differently. Similar to the previous algorithm the correction for the blue channel is calculated by Eq. (10)

$$corrB = \frac{StdLumR + StdLumG + StdLumB}{3 * StdLumB} \,. \tag{10}$$

Finally the correction coefficient $corr\ B'$ for the blue channel is adjusted by Eq. (11)

$$corrB' = corrB * \frac{(StdLumR + StdLumG)/2}{StdLumB} \,. \tag{11}$$

The correction coefficient for the red one is then calculated by first plugging the newly adjusted values of the blue channel, and etc.

3.7. White Patches in YCbCr Color Space

In this method (*WPYCC*), proposed by Wang, Chen and Fuh [9], the image is converted into YCbCr color space, and the correction factors are obtained through Eq. (12):

$$corrR = \frac{Y_{\max}}{R_{avg}} ,\ corrG = \frac{Y_{\max}}{G_{avg}} ,\ corrB = \frac{Y_{\max}}{B_{avg}} \tag{12}$$

where Y_{max} is the maximum value of intensity Y in YCbCr color space.

4. Experimental Setup and Results

The experiment uses Olympus E-P2 digital still camera with high quality lens „Olympus OM-System Zuiko“, 50 mm, f-stop 1:1.4 (the used f-stop is 1:8). All images are taken with maximum camera resolution 4032x3024 pixels in Adobe RGB color space, and under several different AWB camera settings (auto + ten presets for different color temperatures).

The test scenes are shot under different light conditions: daylight, fluorescent light, combination of these two, shadow, tungsten and energy saving lamps. In addition, in professional light box studio images of Macbeth ColorChecker chart [7] (*figure 4(c)* and *figure 8*) are taken. Macbeth chart is an industry standard that provides a non-subjective comparison with a test pattern of 24 scientifically prepared colored squares. Each color square reflects light in the same way in all parts of the visible spectrum, thus maintaining color consistency over different illumination options.

All studio images are captured under six calibrated illumination environments: Illuminant A – tungsten light; Ultralume 30 (U30) and TL84 – fluorescent sources; three types of daylight sources – D50 (equal energy daylight), D65 (average daylight), and D75 (north sky daylight). As ground truth data, the color temperature of illuminants was measured by Chroma meter Konica Minolta CL-200 with measurement precision ±20K (*figure 4(c)* and *figure 9*). Since white balance algorithms are executed before CFA (color filter array) interpolation, color values of the images are taken according to the Bayer filter structure.

Evaluation of the AWB algorithms is done by using two criteria: subjective and objective. The subjective methods are based on visual evaluation and the human perception of the colors in a scene. According to this criteria best results are obtained for the following algorithms: under tungsten light *WPYCC* works better than the others methods (but slightly overexposure of the image, as shown in *figure 5d*), and *SDWGW*$_2$ and Gray world methods also work well (*figure 5*).

Under fluorescent light (*figure 6*) the best results are obtained for *GWT*, *SDWGW* and *WPYCC* algorithms; under the combination daylight+shade the Retinex method surpasses the others; under the combination daylight+fluorescent light the *GWT*, *SDWGW*, *SDLWGW*$_1$, *SDLWGW*$_2$ and *SDL* algorithms work approximately equally well, while *WPYCC* balances the colors well, but increases image brightness.

For energy saving lamps (in this case *Sylvania mini-lynx fast start* lamp with color temperature 2700K) - *figure 4(b)* none of the explored algorithms makes a good white balance (*figure 7*). The main reason for this is that these light sources have very high amplitude spikes ([8], *figure 1(c)*) in their spectrum and this leads to incorrect sensor response and results in incorrect image colors capture.

For images taken of the scattered light in the room (a little shade), some of the algorithms did not provide good results (*figure 8*). The combination of Retinex and Gray world leads to a reassessment of color temperature and the resulting image is bluish, while under Retinex the image is more yellow and saturated than the original. On the other hand the *WPYCC* leads to very heavy overexposure of the final image.

For objective evaluation of the AWB algorithms are used images of the Macbeth color checker card, taken under different calibrated lightning conditions in a professional light box (*figure 9*).

The method proposed by the authors for objective evalu-

Estimated RGB values of Macbeth chart under different Illuminations after AWB algorithms

Gray patches	RGB (Babel)	Illuminant A		U30		TL84		D50		D65		D75	
		4[1]	7[1]	1[1]	7[1]	5.2[1]	6[1]	2[1]	7[1]	5.1[1]	5.2[1]	2[1]	5.1[1]
R	245	200	221	195	194	222	216	208	208	217	217	213	211
G	245	208	234	204	206	220	222	205	219	217	217	212	212
B	242	218	232	212	196	213	216	201	216	217	216	207	215
R	200	174	192	168	167	193	187	179	178	189	188	183	181
G	201	181	204	175	177	192	194	176	189	187	187	184	184
B	201	186	198	177	164	186	188	174	186	190	190	181	188
R	160	145	160	136	135	159	155	145	144	156	156	150	148
G	161	150	169	143	144	158	160	143	153	154	154	150	150
B	162	151	161	137	127	150	155	138	148	154	154	146	151
R	120	105	116	96	96	114	111	101	101	111	110	104	104
G	120	105	118	99	100	112	113	98	105	108	108	105	104
B	121	103	109	91	84	105	107	94	101	107	107	100	104
R	84	58	64	48	47	60	59	52	51	56	56	54	53
G	85	60	68	49	50	60	61	50	54	55	55	54	54
B	86	61	65	49	45	59	59	52	56	59	58	55	57
R	52	26	28	24	24	27	27	26	26	27	27	26	26
G	53	25	28	25	25	27	27	25	27	26	26	26	26
B	54	25	27	26	26	28	28	28	30	28	28	27	28

[1] 1 - GWT, 2 - RM, 3 - GWR, 4 - SDWGW, 5.1 - $SDLWGW_1$, 5.2 - $SDLWGW_2$, 6 - SDL, 7 - WPYCC

ation of the algorithms is the following: since the reflectance of Macbeth card is strictly rated and known, RGB values in Adobe color space from [7] are used as reference data to determine the AWB algorithms accuracy. From each of the grayscale patches of the card are taken regions with 240x150 pixels and their mean values are used for estimation. The results of the two best algorithms for different light sources are shown in the *table*. The criterion for selecting of two best algorithms is that the evaluated values of the RGB components are closest to the references given in the *table*, column RGB (Babel).

The results are different for the different illuminants. In case of Illuminant A (color temperature about 2865K, yellowish-red) and U30 (color temperature about 3000K, yellowish-red) the best result are obtained by Gray world, standard deviation-weighted gray world and white patches in YCbCr color space (1, 4, 7 - the *table*). For Illuminant TL84 (color temperature about 4100K, greenish) best results are obtained through: standard deviation and luminance-weighted gray world algorithms ($SDLWGW_1$ and $SDLWGW_2$) and adjacent channels adjustment by standard deviation and luminance (5.1, 5.2 and 6 – the *table*). Retinex method, $SDLWGW_1$ and $SDLWGW_2$ work better for daylight illuminations (D50, D65 and D75) – the *table*. The *WPYCC* method also provides good results for daylight illuminants, but has a tendency to overexposure of the image, especially for illuminants D65 and D75 (see top 3 RGB values of light grayscale patches from - the *table*: instead of R, G, B equal to 245, 245, 242 obtained results are 240, 255, 255; instead of R, G, B equal to 200, 201, 201 obtained results are 206, 223, 239; instead of R, G, B equal to 160, 161, 162 the obtained results are 169, 182, 192). All the methods have darkened the two darkest patches of the color checker card (underexposure), but still the results are grayscale levels.

5. Conclusion

The best results from the implemented auto white balance algorithms were obtained from GWT, Retinex, standard deviation and luminance-weighted gray world ($SDLWGW_1$ and $SDLWGW_2$ - proposed by the authors) and white patches in the YCbCr color space algorithms. The suggested by authors modification of the Lam's algorithm gives results close to the original method but they are slightly better for most of the tested images. There are problems with white balance mostly for two kinds of color sources – standard illuminant U30 (fluorescent source) and energy saving lamps (another type of fluorescent source). The problem with the first source is that the balanced image is darker than the original (see – the *table*) and the problem with the energy saving lamps is in the incorrect white balance and color reproduction. The tendency is that the energy saving lamps will replace tungsten lamps and that is why the goal of the authors will be development of automatic white balance algorithms which work correctly with this kind of light sources.

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Manuscript received on 13.10.2011

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