

ELIMINATION OF COLOR FRINGES IN DIGITAL PHOTOGRAPHS CAUSED BY LATERAL CHROMATIC ABERRATION

V. Kaufmann, R. Ladstädter

Institute of Remote Sensing and Photogrammetry Graz University of Technology, Austria viktor.kaufmann@tugraz.at

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ABSTRACT

The effects of (monochromatic and chromatic) lens aberrations in optical imaging are well documented in the literature. These geometrical imperfections are caused by the physical parameters of the optical system (lens) of the photographic camera and apply to both analog and digital cameras. All these aberrations produce lateral distortions (geometric errors) and/or longitudinal distortions (image blur) in one way or another. In this paper we focus on the elimination of the effect of lateral chromatic aberration within a post-processing step after image acquisition. This task has already become a vital topic with the advent of digital (consumer) cameras. Many references can be found in the World Wide Web. Several methods, from simple heuristic to more stringent ones, are proposed by the user community. Since the usage of digital consumer cameras (SLR or compact cameras) in documentation and mapping of cultural heritage is becoming more and more wide-spread, the present topic should be discussed in more detail. Color fringes are inherent to all analog and digital (color) photographs taken by cameras for which chromatic aberration is not sufficiently corrected for. The width of color fringes, mainly introduced by lateral chromatic aberration, is smallest around the image center and greatest in the corners of the photographs. The authors have developed a computer-based procedure to precisely determine the geometric distortions of the red and blue image channel (plane) in comparison to the green reference channel. Least-squares matching is employed at distinct corner points found by an interest operator in order to measure point displacements. The paper also describes how these measurements can be carried out using a commercial software, i.e. PhotoModeler 5.0. In a first approximation the three RGB color channels differ in scale, i.e. they are radially displaced. Originally, the *DistCorr* software has been developed in order to compensate for lens distortion to obtain perfect central-perspective images. The software mentioned was readily modified for correction of lateral chromatic aberration. As a result, the geometrically re-scaled red and blue image planes are registered to the green one. The amount of image displacement of the two color channels can be specified as an additive correction to the linear parameter of the radial-symmetric lens distortion formula. Lateral color fringes can thus be eliminated to a great extent with this simple method. This paper also presents examples of practical investigations. Three lenses (17 mm, 20 mm, 50 mm) of a digital consumer camera, i.e. a Nikon D100 SLR with 6 Megapixels, were analyzed. The results obtained are presented numerically and graphically. An outlook on further improvements in the elimination of color fringes is given at the end of the paper.

1. INTRODUCTION

In 2003 a Nikon D100 digital SLR camera was acquired, and subsequently a fully digital photogrammetric workflow using a digital photogrammetric workstation ISSK of Z/I Imaging was set-up to accomplish close-range photogrammetric projects. The reason why color fringes exist is well-known (see next chapter). High-quality lenses are designed to meet special interactive three-dimensional (3D) mapping of architectural requirements, e.g. that of professional photographers or the ensembles and production of color orthophotos of facades. surveying and mapping community. Other applications related to glacier monitoring in high to mountains (Kaufmann and Ladstädter, 2004). Because of the smaller size of the CCD area of most of the consumer cameras compared to the image format of 35 mm photography, wide-angle or even fish-eye lenses must be used in order to enlarge the field angle. Digital photographs taken with lenses of this kind are very much prone to color fringes which can be clearly recognized in the image corner areas of the photographs. These color fringes become obvious and even visually disturbing when producing orthophotos of facades photographed in oblique viewing direction. In this case unwanted magnification of the existing color fringes can be caused by the ortho-rectification process. Moreover, 3D mapping is hampered by chromatic image blur and differences of homologous points (regions) located outside the image centers, and color-based image analysis (visual and also automatic classification) is rendered more difficult or even made impossible.

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chapter).

High quality lenses are designed to meet special requirements, e.g. that of professional photographers or the surveying and mapping community. These lenses are expensive to produce. Lenses of most of the digital (and also analog) consumer cameras are of lower quality due to larger lens aberrations, thus reducing production costs. One of the crucial quality factors of lenses is the correction of chromatic digital aberration(s). Since the effect of chromatic aberrations cannot be eliminated by photographic techniques, e.g. by using small apertures (high f-stop number), it is inherent to all photographs taken with such a lens. (Remark: Only longitudinal chromatic aberration can be reduced to a high degree by stopping down.) The elimination of (lateral) chromatic aberration as a post-processing step in digital photography is exhaustively discussed in the World Wide Web (WWW). Some interesting references of websites are given at the end of the paper. Scarce information is available, however, from a photogrammetric point of view.

2. THE NATURE OF CHROMATIC ABERRATIONS

The design of optical systems (photographic lenses) is complex, and especially lens aberrations must be considered in the image formation process. Hecht 1987 and the Manual of Photogrammetry (Slama, 1980) are two excellent sources for obtaining basic insights into the problems of geometric optics and the design of (refractive) optical systems. The two main types of aberrations are (1) *monochromatic aberrations* (= Seidel aberrations, see Slama 1980, 119-124, not considered in this paper) and (2) *chromatic aberrations*, which are due to the dependency of the refractive index (n) of the lens on the

wavelength (λ). Actually, monochromatic aberrations are also chromatically influenced.

Two types of chromatic aberrations must be considered.

2.1 Longitudinal (axial) chromatic aberration

Incident rays of white light parallel to the optical axis of a lens are not focused in one image point (= focus), but different foci exist (see Figure* 1) for each color (wavelength of the electromagnetic spectrum). Rays of light of shorter wavelength, i.e. blue (B), are more strongly refracted than rays of longer wavelengths, i.e. green (G) or red (R). This is known as dispersion. In other words: The sequence of foci along the optical axis is color dependent, starting with violet-blue (closest to the convex lens), followed by the other colors of the spectrum and ending with red (farthest to the lens). Image formation can only be done at a specific image plane setting. The image plane in Figure 1 is intentionally positioned at the focus of the green light (FG). The G rays are focused in one distinct point, whereas all other-colored rays produce respective color patches in the image plane, the latter causing image blur. This phenomenon holds not only for axial image points but also for off-axis points. (Remark: This is why the term longitudinal is more appropriate than axial.)

2.2 Lateral (oblique) chromatic aberration

Due to the above mentioned fact that focal length varies with wavelength, the respective optical (lateral) magnification changes accordingly. This is often referred to as *chromatic difference in magnification*. Referring to the example of Figure 1, the magnification increases with longer wavelength (cp. Hecht 1987, p. 233, Fig. 6.33), whereas the respective image scales of the chromatic images in the image plane decrease (see Figure 2). If the mean focus is set for the G channel then (1) both images of B and R are blurred, (2) the image scale of the R channel is smaller than the G channel, and (3) the image scale of the B channel is larger than the G channel. For photographic lenses the actual chromatic order of the dispersed rays depends on the design of the optical system (cp. the results of chapter 3). Lateral chromatic aberration causes radial-symmetric point displacements, and the introduced geometric errors can be described in a first approximation as the chromatic difference of the linear term (K_0) of lens distortion. (Remark: The correction term is a linear function of the radial distance.) The physical reality is more difficult, however, as has already been mentioned. Higher-order chromatic errors can be described sufficiently by equivalent correction terms K_1 , K_2 , and K_3 . Lateral chromatic aberration causes color fringes, which are visible at high-contrast edges at off-radial directions. Since lateral chromatic aberration causes deterministic image displacements, it can be corrected for in a post-processing step, presuming that the image (photograph) is in digital format. Image blur due to longitudinal chromatic aberration cannot be reversed in general, but it can be reduced by stopping down the lens as stated earlier. In the following we describe how to measure, model and eliminate the effect of lateral chromatic aberration.

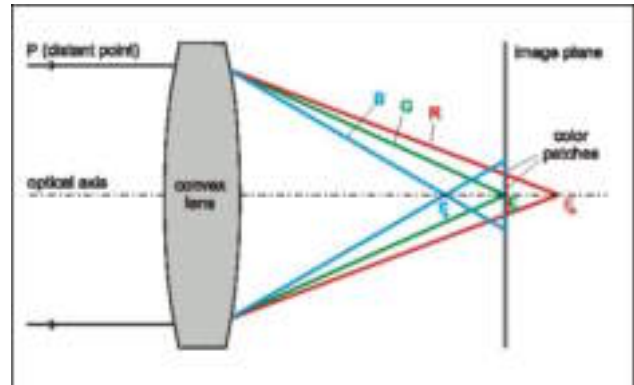


Figure 1. Longitudinal (axial) chromatic aberration

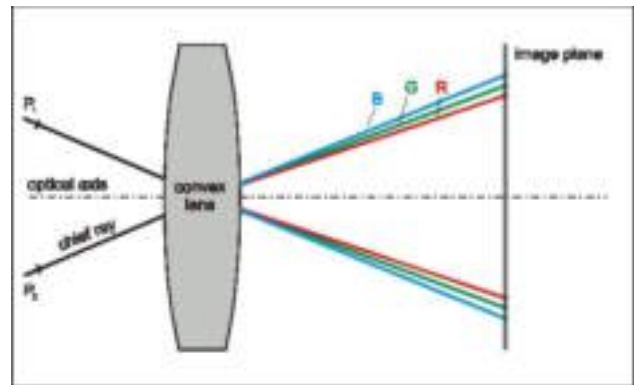


Figure 2. Lateral (oblique) chromatic aberration

3. MEASUREMENT OF LATERAL CHROMATIC ABERRATION USING PLANAR TARGET FIELDS

In this chapter we describe two different approaches of measuring the effect of lateral chromatic aberration. The general task is to co-register the R and B channels onto the G channel by measuring corresponding points in the three color channels (planes). These points should be numerous and well distributed over the whole image format. Since color misregistration due to chromatic aberration is small and the accuracy of manual measurement on the screen is rather limited (up to $\frac{1}{4}$ of a pixel), the measurements should be carried out automatically by digital techniques. As a result, displacement vector fields describing the geometric differences between the three RGB channels can be obtained.

Practical experiments have been carried out using a Nikon D100 digital SLR camera (see Table 1) with three different interchangeable lenses, i.e., a Tokina AT-X AF 17 mm aspherical 1:3.5, a Nikon AF Nikkor 20 mm 1:2.8 D, and a Nikon AF Nikkor 50 mm 1:1.8 D.

camera type	digital SLR camera with bayonet mount
sensor	CCD array
resolution	3008 × 2000 pixel
pixel size	7.8 × 7.8 μm
color information	Bayer pattern (see Leberl et al., 2002)
digital image data	uncompressed RGB-TIFF (18 MB)
data storage	IBM Microdrive

Table 1. Main characteristics of the Nikon D100 camera

* Figures in color, please see

<http://www.geoimaging.tugraz.at/viktor.kaufmann/publications.html>

All photographs were taken with focus set to infinity. Automatic image sharpening was switched off in order to avoid additional geometric errors. Theoretically, one single digital color photograph is sufficient for measuring and modeling the effect of (lateral) chromatic aberration.

3.1 Least-squares-matching between color channels

The first approach uses the highly accurate least-squares-matching (LSM) technique for transferring points from the G channel to the R and B ones. Since well-defined "corner points" with high contrast are best suited for precise image matching, a black-and-white target field with corners, such as the calibration target field of PhotoModeler 4.0 (EOS, 2000), should be used (see Figure 3). This planar field (size of plot:

1.20 × 0.85 m) was captured several times from a perpendicular viewing angle. Full coverage of the image format with the calibration pattern was assumed. The aperture was set to the minimum (highest f-number) in order to obtain sharp photographs. (Remark: From a photogrammetric point of view, of course, the size of the calibration field should be much larger.)

In a pre-processing step the color photographs must be split up into their single channels (see Figure 4). The G channel is selected as the geometric reference source, since it is the image channel which is generally used for camera calibration and holds the best signal-to-noise ratio. In this channel all corner points were automatically detected using the interest operator of Förstner. These points were then transferred into the R and B channels using LSM. The chromatic displacements are typically rather small (in the range of a few pixels). In addition, there are practically no geometric distortions in the corresponding image patches. The measuring accuracy achieved by LSM is thus extremely high (a few hundredths of a pixel). The results of these measurements are chromatic displacement vectors (pointing from G to R, and G to B) for all corner points.

3.2 Automated feature detection (using circular targets)

PhotoModeler 5.0 (EOS, 2003) provides a new camera calibration target field, which is of quadratic size. It shows a regular grid of black circular targets. This grid was modified by adding two additional columns of targets on the left and right sides to better fit the rectangular image format (see Figure 5). The target field was plotted in the size 1.40 × 1.00 m.

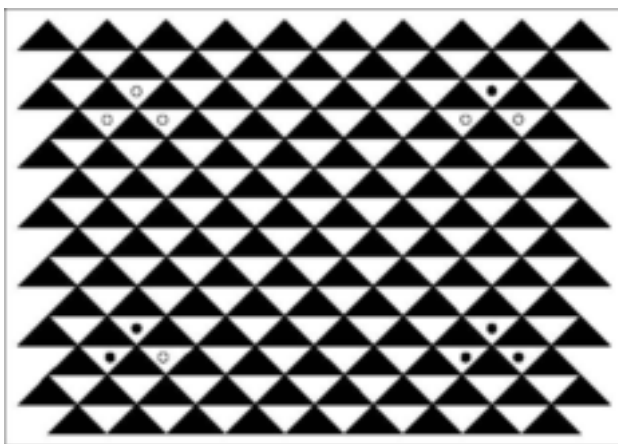


Figure 3. Planar calibration field of PhotoModeler 4.0

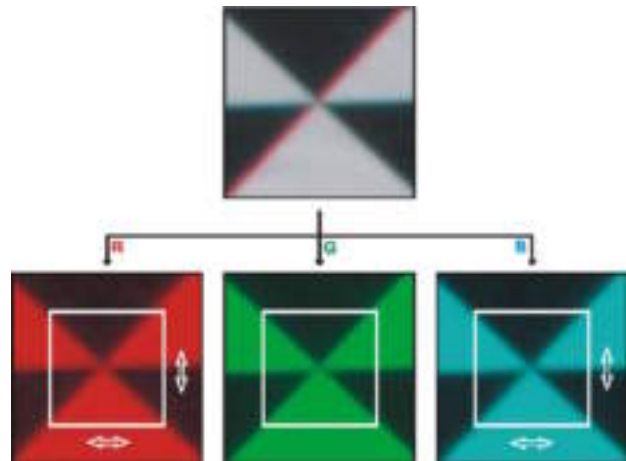


Figure 4. Measuring of corresponding points in the RGB channels (17 m lens, window size 70 × 70) by means of LSM.

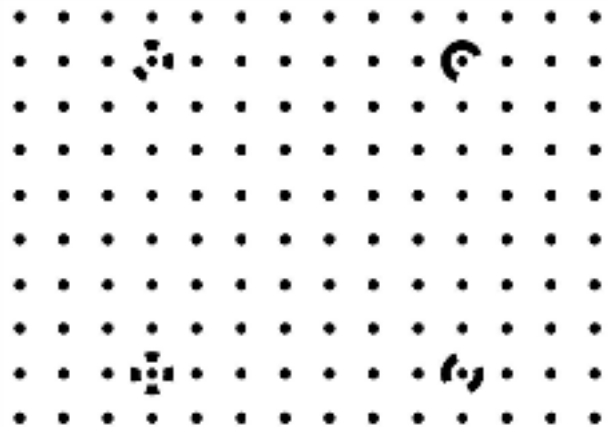


Figure 5. Modified calibration field of PhotoModeler 5.0

PhotoModeler 5.0 offers excellent tools for precisely measuring image coordinates of circular targets. In order to save time, the computation of the effect of lateral chromatic aberration was done within the framework of a (periodic) camera calibration. A camera calibration is first performed with the G channel. The calibration is then repeated using the same frames, but taking the other two channels R and B. In order to get a first estimation of the scale difference between the RGB channels, the camera parameters of the G channel are imported into the other two projects. In the bundle adjustment (which has to be repeated after the initial calibration step) all camera parameters must be kept unchanged, except the focal length. Based on this assumption the difference in scale of the three colour channel can be easily computed by calculating the relative change of the G focal length. Image coordinates of all measurements can be exported for further external processing. Displacement vectors can be computed as described in the previous section. Highest accuracies were obtained for those photographs with the least perspective distortion. Figures 6-11 show the results obtained for the lenses available. The image displacements depicted show graphically the offset of the R and B channel in respect to the G channel. In our experiments we merged the measurements of at least a single data takes for improving the quality of the final result.

Both approaches described have been tested and give similar results, although they use different matching techniques (area-based vs. feature based).

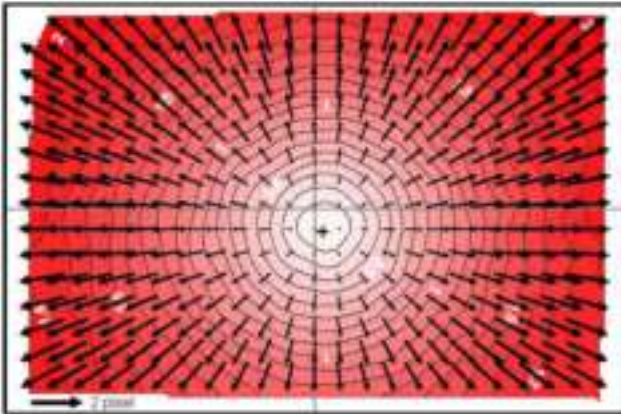


Figure 6. Interpolated displacement vectors: R channel, 17 mm lens, 411 points measured in 3 photographs.

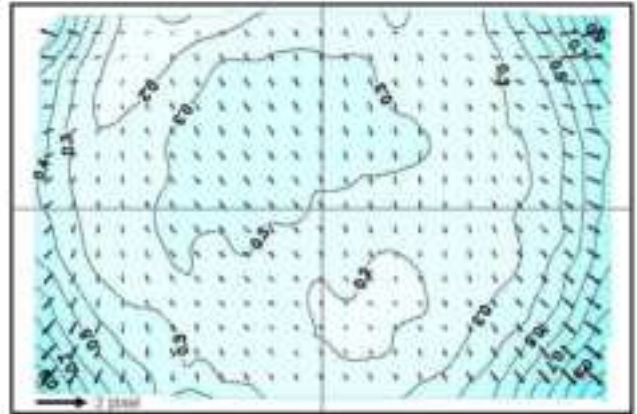


Figure 9. Interpolated displacement vectors: B channel, 17 mm lens, 411 points measured in 3 photographs.

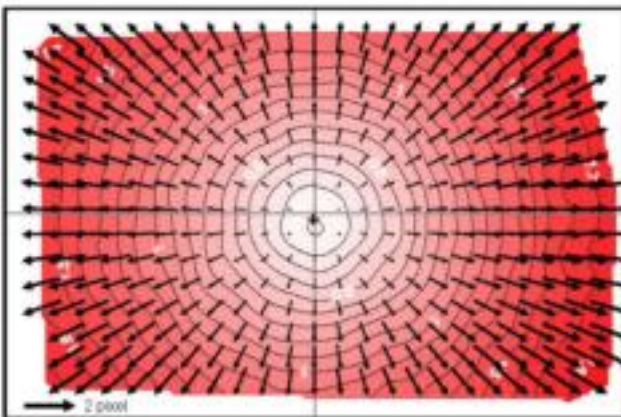


Figure 7. Interpolated displacement vectors: R channel, 20 mm lens, 381 points measured in 3 photographs.

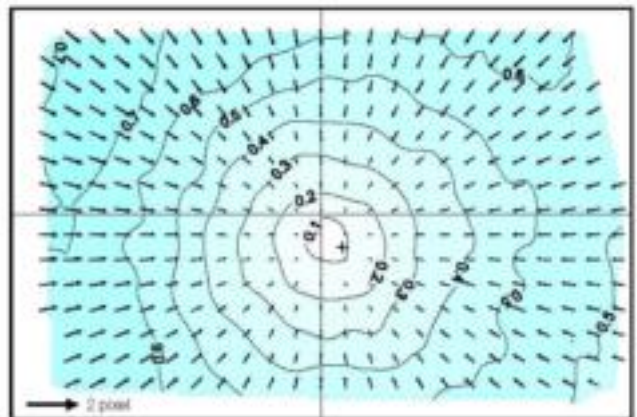


Figure 10. Interpolated displacement vectors: B channel, 20 mm lens, 381 points measured in 3 photographs.

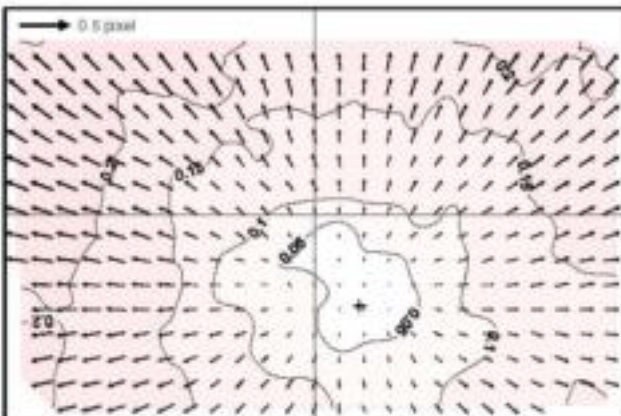


Figure 8. Interpolated displacement vectors: R channel, 50 mm lens, 344 points measured in 3 photographs.

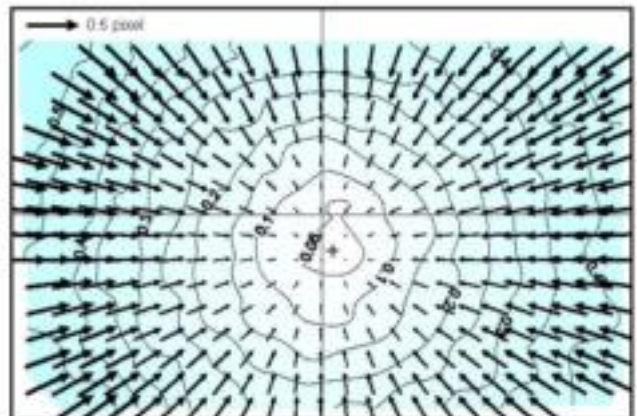


Figure 11. Interpolated displacement vectors: B channel, 50 mm lens, 344 points measured in 3 photographs.

4. MODELING OF THE EFFECT OF LATERAL CHROMATIC ABERRATION

From an image processing point of view the elimination of the effect of lateral chromatic aberration can be accomplished by two independent image-to-image registration steps. Both channels R and B must be resampled to geometrically fit the G reference channel. Appropriate modeling of the geometric distortions measured must first be performed. Analyzing the spatial structure of the displacement vectors of Figures 6-11, we

can draw the following conclusions: (1) the chromatic misregistration is generally more or less radial-symmetric; (2) the amount of radial image displacement is not necessarily a linear function of the radial distance; (3) the geometric center point (= location where there is no chromatic image displacement, see crosses in the respective Figures) is likely not to coincide with the principal point (approx. image center) of the G channel; and (4) chromatic misregistration may in some instances be of a general geometric type, e.g. non-radial-symmetric. It should be mentioned that chromatic

misregistration is not only due to lens characteristics but it can also be introduced by the electronics (CCD array, color interpolation, anti-aliasing, etc.) of the digital camera.

In a first attempt we selected a simple 3-parameter coordinate transformation. Image shift (Δx , Δy) and scale difference ($dK0$) were calculated by means of least-squares adjustment for each combination of image channels (G-R and G-B, respectively). The numerical results are shown in Table 2.

lens	$dK0$ (R)	$dK0$ (B)	RMSE (R/B)
17 mm	0.001407	-0.000211	0.092/0.150
20 mm	0.001251	-0.000524	0.049/0.059
50 mm	0.000141	-0.000318	0.026/0.030

Table 2. Modeling of the effect of chromatic aberration

Based on the numerical values shown in Table 2, e.g., the corner points (radial distance = 1800 pixel) of the 20 mm R channel are radially shifted outwards by 2.25 pixels, whereas the B channel is shifted radially inwards by 0.94 pixel. This means that both channels differ geometrically by more than 3 pixels in radial direction. This distance is a measure for lateral chromatic aberration. The 50 mm lens shows the best performance in respect to lateral chromatic aberration. Chromatic misregistrations are less than 0.25 pixel for the R channel and 0.57 pixel for the B channel. RMSE is approx. 0.03 pixel for the 50 mm lens. In all examples the RMSE of the R channel is better than the corresponding B channel. (Note that the high RMSE given is mainly caused by the simplified model.)

5. ELIMINATION OF THE EFFECT OF LATERAL CHROMATIC ABERRATION

A first software-based elimination of the effect of (lateral) chromatic aberration has been realized using the in-house developed computer program *DistCorr*, which was already available at the time of this study. Originally, *Distcorr* was developed in order to eliminate geometric distortions in digital photographs with the final goal of obtaining ideal perspective images, i.e., where (1) the principal point coincides with the image center, (2) the pixels are exactly square, and (3) neither radial-symmetric nor decentering lens distortions exist. The software *DistCorr* is written in C language based on the Intel © IPP Library.

The elimination of the effect of chromatic aberration is now an additional feature of this software. In a first release of the new software, chromatically induced geometric distortions can be simply modeled by adding the respective correction terms to the linear term $K0$ of the radial-symmetric lens distortion function (cp. Table 2), i.e., $K0$ (R) = $K0$ (G) + $dK0$ (R), $K0$ (B) = $K0$ (G) + $dK0$ (B), and $K0$ (G) = $K0$ (G). (Remark: The sign of the correction term depends on the definition of the lens distortion formula.)

A batch processing capability of the software enhances the ease of work, e.g., all images (TIFF) of a given directory can be processed automatically with the same parameter settings. Default parameters of several digital and analog cameras, e.g. Rolleiflex 6006 réseau, with their respective lenses are provided for direct use. The elimination of the effect of chromatic aberration is routinely carried out in all close-range photogrammetric projects where high-quality color (RGB) images are needed.

6. EXAMPLES

In this chapter, we demonstrate the elimination of the effect of chromatic aberration using photographs of typical architectural scenes. Even using the simplified approach described above improves image quality significantly. This is especially true for those digital photographs taken with wide-angle lenses (see examples of Figure 12).

We also tried to measure the chromatic aberration directly in photographs of natural scenes without using a calibration target. Of course, this is only possible with the LSM approach (there are no targets in the scene). Depending on the image content, the results were generally in good accordance with the results obtained with the calibration target fields. However, the noise level of the measurements is much higher because of the lower quality of the extracted interest points of a natural scene. If the image contains many pure color tones, as in the "painted house" example (see Figure 13), LSM even produces a great number of mismatches, which makes a further modeling of the chromatic aberration impossible. The reason for this problem is the inversion of gray values in the different color channels of the image. For example, a green feature looks bright in the G channel but dark in the R channel. For this image, interest points had to be selected manually in more or less "colorless" regions in order to produce a reasonable result at all.

We therefore strongly recommend the use of black-and-white targets for the determination of chromatic aberration. This can be done either during an extended camera calibration procedure or on-the-job with special targets deployed individually in the scene of interest. Nevertheless, the determination of chromatic aberration for individual images is possible without the use of any targets whenever highest accuracy in color reproduction is not needed.



Figure 12. Examples for the elimination of color fringes in digital photographs. The photographs were taken with a Nikon D100 digital SLR camera using a 20 mm lens. The image chips shown (window size 150×150) were cropped from areas near the image corners. The left column shows the original image data, whereas the right one is corrected for. The last example was taken from the photograph (Figure 13) shown below.



Figure 13. Color photograph (Nikon D100, 20 mm lens) showing a painted facade of a medieval building, Graz, Austria.

7. CONCLUSIONS AND OUTLOOK

In this paper we described a procedure of how to accurately measure, model and eliminate color fringes in digital photographs caused by lateral chromatic aberration. The results obtained are highly promising even using a very simple geometric model. Further developments will be focused on better modeling of the chromatic displacement vectors measured. Practical experiments will be carried out in order to address the dependency of the model parameters on object distance and focusing. A final goal is to develop a comprehensive software tool which combines the measuring and modeling steps.

The calibration tool of PhotoModeler 5.0 could be easily extended for simultaneous target detection in the three color channels. This would facilitate the modeling and also the elimination of the chromatic aberration effect in color images.

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