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Automated Calibration of Fisheye Camera Systems and the Reduction of Chromatic Aberration

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Keywords: Camera calibration, fisheye camera, chromatic aberration, panorama, omni-directional imaging

Summary: This paper reports on the camera calibration procedure developed at CycloMedia and its modification for the reduction of chromatic aberration for further improvement of CycloMedia's main product: 360-degree panoramic images called Cycloramas. These Cycloramas are used for a variety of applications for a wide range of clients including municipalities, provinces, housing corporations, estate agents, and insurance companies.

For the production of Cycloramas CycloMedia has developed a car-mounted camera system that makes use of a fisheye lens. The adopted fisheye camera model and the procedure for automated camera calibration are presented in the paper. The calibration software performs a least-squares adjustment for the estimation of the camera parameters that describe the relation between the spatial direction of a ray and its projection in the image plane, i. e. the interior orientation.

The calibration procedure has been applied for each colour band of a test data set in order to reduce chromatic aberration. Colour artefacts were still present in the Cyclorama constructed using the per band calibration parameters. The conclusion is that the colour aberrations in the images under consideration cannot be reduced significantly with this approach and that not only lateral chromatic aberration plays a role. Furthermore, the nature of this chromatic aberration is to be studied in more detail in order to come to a final solution for its reduction.

Zusammenfassung: *Automatische Kalibrierung von Fisheye-Kameras und Reduzierung der chromatischen Aberration*. Der Artikel beschreibt ein Verfahren zur Kalibrierung von Fisheye-Kameras, das bei CycloMedia entwickelt wurde, sowie Untersuchung zur Verringerung der Effekte der chromatischen Aberration zur weiteren Verbesserung von CycloMedia's 360° Panoramabildern. Diese sogenannten Cycloramas werden in der Praxis für ein Vielzahl von Anwendungen eingesetzt, beispielsweise bei Gemeinden, Wohnungsbaugesellschaften, Immobilienmaklern und Versicherungsgesellschaften.

Für die Produktion von Cycloramas hat CycloMedia ein Kamerasystem mit einem Fisheye-Objektiv entwickelt. Das Kameramodell und das Verfahren für die automatisierte Kamerakalibrierung werden in diesem Artikel dargestellt. Die Software für die Kalibrierung benutzt eine Kleinste-Quadrate-Ausgleichung für die Schätzung der Kameraparameter, die die Relation zwischen der räumlichen Richtung eines Strahls und seiner Projektion in der Bildebene beschreiben. Das Kalibrierverfahren kann für jeden Farbkanal separat eingesetzt werden, um Effekte der chromatischen Abweichungen zu verringern. Die Resultate von Testmessungen zeigen allerdings, dass die Effekte der chromatischen Aberration mit diesem Ansatz nur partiell beseitigt werden können. Daher wird die chromatische Aberration inclusive ihrer nichtradialen Anteile detaillierter betrachtet.

1 Introduction

1.1 *Background*

Boosted by the change from analogue to digital imaging, there is a growing interest in panoramic imagery. This is not only due to the fact that tools for the creation of digital panoramas have become a commodity. The main advantage of panoramas, and especially of omni-directional or 360-degree panoramas, is found in the variety of their

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Fig. 1: CycloMedia car with camera system.

applications. For many applications the image geometry plays a major role. Therefore, calibration of the camera-lens combination utilised for capturing the imagery is of utmost importance, especially for 3D measurement applications.

CycloMedia is a company that has omnidirectional panoramas, so-called Cycloramas, as its main product. The Cycloramas are created from two fisheye images with a field of view of 185 degree each. The camera is turned 180 degree between the two shots. The cycloramas are systematically acquired from all public roads with a standard interval of 10 meter. Furthermore, the imagery is geo-referenced and commonly delivered with tools for a seamless integration with the customers GIS-application. Currently, CycloMedia has 35 cars with a dedicated camera system mounted on the roof (Fig. 1). This system has been developed in-house, including the software for processing the approximately 6 GB of image data daily delivered by each car.

A Cyclorama can contain image data for the full sphere stored in a panorama image of 4800 × 2400 pixels, corresponding to 360° × 180°. Thus, on the horizon, the angular resolution is 0.075° per pixel. For efficiency reasons the opening angle in vertical direction is reduced with 20 % removing the major part of the car. An example is shown in Fig. 2. For each pixel the spatial orientation of the associated ray is known in the camera system and can be directly computed from its location in the image. Obtaining a panorama with this property from two partly overlapping fisheye images requires the camera-lens combination to be calibrated, i. e. the interior orientation is to be known. This calibration and its dependency on wavelength is the topic of this paper.

1.2 *Previous work*

In the last years there is a growing interest in panoramic imaging and photogrammetric use of panoramic imagery. This is reflected in the success of ISPRS workshops on this topic[1]. Several papers have been published on the calibration of panoramic camera systems that make use of a fisheye lens. Some approaches are based on the use of straight line features (Amiri Parian & Grün

Fig. 2: Sample Cyclorama.

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[1] Website of the last workshop: http://www2.informatik.hu-berlin.de/sv/pr/PanoramicPhotogrammetryWorkshop2005/

2005), mostly a point field is used of which the 3D coordinates of the targets are known (Kannala & Brandt 2004, Schneider & Schwalbe 2005, Schwalbe 2005). The calibration method presented here is fully automated in the sense that it detects point features using image processing and automatically finds corresponding points between overlapping images. Spatial coordinates of the targets are not required. Furthermore, the calibration is automated which is the main improvement to the procedure as described in (van den Heuvel et al. 2006).

Recently, some investigations into the elimination of lateral chromatic aberration have been conducted (Kaufmann & Ladstädter 2005, Luhmann 2006, Schwalbe & Maas 2006). These studies aim at image enhancement or photogrammetric measurement precision improvement. Only in (Schwalbe & Maas 2006) chromatic aberration of a fisheye camera system is considered. In all approaches a calibration procedure is applied separately for each colour band instead of only one band, usually green. Thus, a set of calibration parameters is determined for each colour band. In this paper we apply the same approach using the calibration method developed in-house.

1.3 *Paper content*

In section 2 the camera model adopted by CycloMedia is presented as well as the camera calibration procedure developed in-house. The precision of the calibration is demonstrated with an example. In section 3 the nature of chromatic aberration is explained and how we use our calibration procedure for determining lateral chromatic aberration. An example shows its limited applicability and how a significant reduction is obtained with a manual approach. The paper finishes with conclusions in section 4.

2 Automated camera calibration

2.1 *The camera model*

In (Kannala & Brandt 2004) an overview of different camera models is given. The perspective projection of a pinhole camera is described with:

$$r = f \tan\theta \tag{1}$$

where

r = distance image point – principal point
f = focal length
θ = angle between optical axis and incoming ray

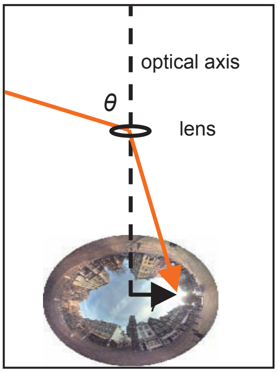

Fig. 3: Fisheye projection (schematic).

For a fisheye lens the straightforward so-called f-theta mapping (Kumler & Bauer 2000) is most common and used here. This projection is also called equi-angular (Schwalbe & Maas 2006) and equidistance projection (Kannala & Brandt 2004):

$$r = f \cdot \theta \tag{2}$$

The parameters r and θ are depicted in Fig. 3. The design of the fisheye lens used here is approaching this relation within a tolerance of ±6%, according to the specifications of the manufacturer. We model the deviations from the relation in (2) with a polynomial:

$$r = f \cdot \theta \cdot (1 + p_2\theta^2 + p_3\theta^3 + p_4\theta^4 + p_5\theta^5) \tag{3}$$

The number of parameters to be estimated (the order of the polynomial) can be set by the user. Next to the parameters f and p in (3), the camera model is complete with the parameters (x_p, y_p) representing the location

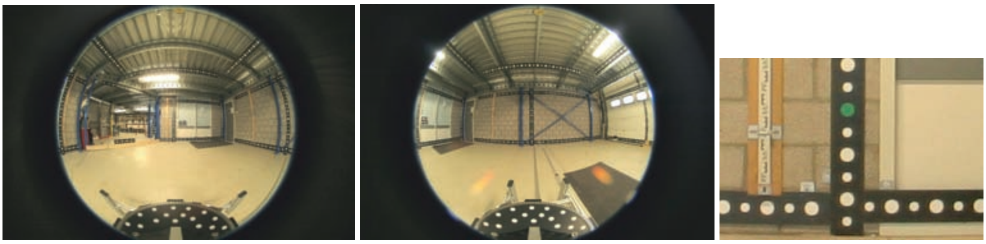

Fig. 4: Two sample calibration images and enlargement of center of left image.

of the principal point. For an image point with location (x, y), r is computed as follows:

$$r = \sqrt{(x - x_p)^2 + (y - y_p)^2} \tag{4}$$

To compute the spatial direction vector of a ray in space associated with an image point, an iterative procedure is applied based on equations (3) and (4) to find angle θ. The angle φ in the image plane found with:

$$\varphi = \arctan\left(\frac{y - y_p}{x - x_p}\right) \tag{5}$$

Equations (4) and (5) define the transformation from Cartesian to Polar co-ordinates in the image plane. The inverse of equation (3) represents the step to a spatial direction in spherical co-ordinates (φ, θ).

2.2 *The calibration procedure*

Before the camera is calibrated the fisheye lens is mounted, focussed, and fixed in a specially designed frame in order to guarantee the long-term stability of the interior orientation. The procedure for the calibration of a fisheye camera consists of the following steps:

1. Acquisition of four images in a calibration room taken at 90° horizontal angles. The room contains approximately 500 circular targets, two sample images are shown in Fig. 4.
2. Automatic detection and localisation of the target images with sub-pixel precision.
3. Automated establishment of correspondence between the tie points of the four images.
4. Least-squares adjustment for camera parameter estimation. Apart from the camera parameters, a horizontal yaw angle is estimated for each image except one. Furthermore, one roll and one pitch parameter are estimated. The mathematical model consists of two observation equations per point measured: one for the horizontal and one for the vertical angle.

Target detection

For detection of point features several methods exist (van Vliet et al. 1988). We implemented a detection scheme based on finding closed contours. Making use of the green image band, gradients for each pixel are calculated in 4 directions (horizontal, vertical and 2 diagonals) using a Sobel kernel. Then the edge angle is defined along the smallest gradient of the set. The edge strength is the gradient value which is perpendicular to the smallest gradient value.

The next step is to check for each pixel whether it lies between 2 edges with opposite angles. If this is true in all 4 directions, the pixel is marked as a candidate for a target. Next, it is tested whether the edges of the candidate are connected to form a closed contour. The contour is found by following the edges. Then attributes for this candidate are gathered, like the location of the center of the contour, and the minimum and maximum distance of the center to the contour. Candidates where the difference of these distances exceed a threshold are rejected. Also other attributes are investigated, for instance the mean RGB values of the target, which are used to classify the targets as white or green. In the calibration room 40 of the 500 targets are green. Identification of these targets greatly simplifies the next step in the procedure: correspondence.

Correspondence and parameter estimation

For the identified green targets the spatial directions of the associated light rays is computed using rough approximations for the camera parameters and camera orientation angles. The accuracy of the computed horizontal and vertical angles is in the order of 0.1 radians. Targets in different images that have approximately the same spatial direction correspond to each other. Using the green targets only, the camera parameters are estimated with exception of the lens distortion, which cannot be estimated accurately from this sparse point field. With the resulting improved values of the camera parameters the spatial directions of all targets are computed with an accuracy better than 0.01 radians. Then for all targets correspondences are found in the same way as for the green targets. Again a least-squares adjustment is performed, now using all targets and estimating all camera parameters. Targets that show large residuals are removed one by one, until the largest residual drops below a threshold currently set to 1 pixel.

2.3 *Example*

The procedure above is regularly applied at CycloMedia for the calibration of her 35 camera systems. The results of the least-squares adjustment of a sample calibration are summarised in Tab. 1.

Tab. 1: Adjustment results: first step using green targets only, second step using all targets (formal standard deviation between brackets).

	1. Green targets only	**2. All targets**
# targets	34	698
σ estimated (pix)	0.18	0.24
Roll (deg)	– 0.124 (0.011)	– 0.123 (0.003)
Pitch (deg)	0.270 (0.050)	0.275 (0.010)
Yaw1 (deg)	90.101 (0.040)	90.107 (0.009)
Yaw2 (deg)	0.339 (0.037)	0.239 (0.008)
Yaw3 (deg)	180.209 (0.041)	180.213 (0.009)
x_p (pix)	1721.38 (0.92)	1721.70 (0.16)
y_p (pix)	1135.33 (0.96)	1134.87 (0.41)
f (pix/rad)	757.94 (0.15)	758.73 (0.60)
p_2	–	0.00017
p_3	–	– 0.0419
p_4	–	0.0449
p_5	–	– 0.0165

Roll and pitch are the angles of the camera system relative to the vertical rotation axis. The yaw of the first image is set to 270 degree. Only the green colour band of the imagery has been used. Note that more than the 500 artificial targets have been used, also other features than artificial targets are detected and help in improving the precision of the results. Furthermore, it is interesting to note the increase in standard deviation of the focal length f as a consequence of the introduction of the lens distortion parameters p that show considerable correlation with the focal length f.

3 Chromatic aberration

3.1 *What is chromatic aberration?*

Chromatic aberrations are imperfections in the imaging properties of a lens due to the dependency of the refractive index of the lens material on the wavelength of the light. The two main types of chromatic aberrations are longitudinal (or axial) and lateral (or oblique) aberration (Fiete 2004) and (Kaufmann & Ladstädter 2005).

Longitudinal aberration results in a focal length that is wavelength dependent. In other words, it is not possible to focus all wavelengths at one position of the image plane (Fig. 5). Lateral aberration results in a wavelength dependent radial displacement of an image point that, at least approximately, leads to a wavelength dependent image magnification (Fig. 6). In this paper we con-

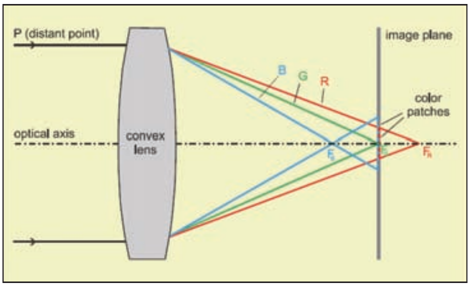

Fig. 5: Longitudinal aberration.

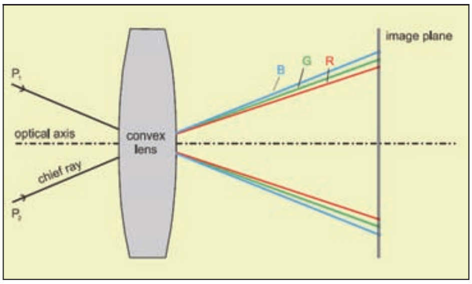

Fig. 6: Lateral aberration.

centrate on the latter type of aberration because it is the most prominent type in the imagery at hand.

3.2 *Determining lateral chromatic aberration*

As demonstrated in (Kaufmann & Ladstädter 2005), (Schwalbe & Maas 2005), and (Hastedt et al. 2006), lateral chromatic aberration can be determined by applying a standard camera calibration to each of the three colour bands. The use of a separate set of camera calibration parameters for each colour band in further processing aims at the elimination of the visually apparent lateral aberration (Fig. 7; note that a calibration field with black targets on a white background was used and not the test field described in section 2). However, as shown in the example in the next section, this procedure was not successful for the imagery under consideration.

3.3 *Example*

Each colour band of four images with 90 degree horizontal angular separation has been measured with both the CycloMedia semi-automatic measurement tool and PhotoModeler's automatic target detection. The measurement results of 94, respectively

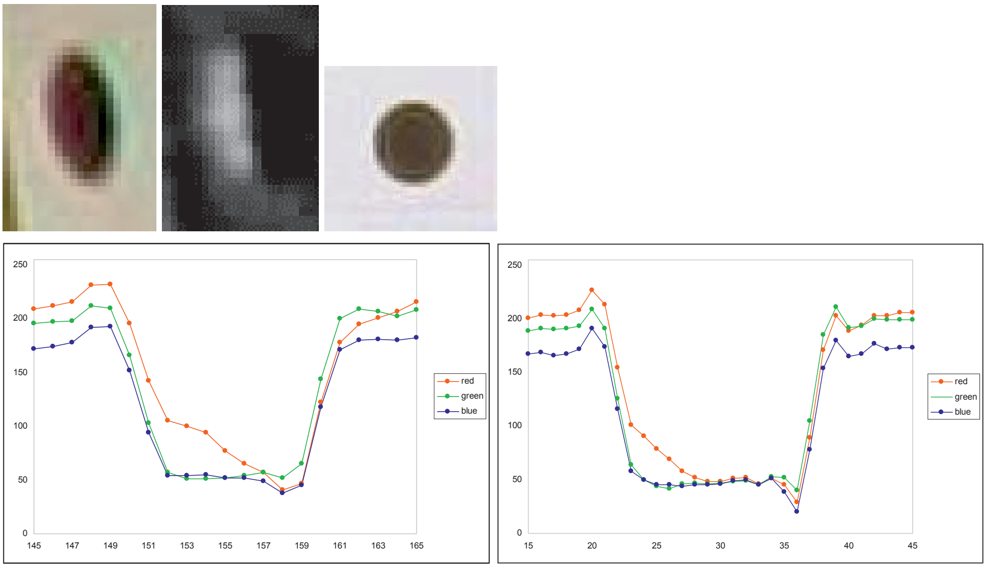

Fig. 7: Sample target (small) located close to the right image border, top-left: original, top- middle: red minus green band (stretched), top-right: target in image centre, bottom: RGB profile in column direction of a small and a large target.

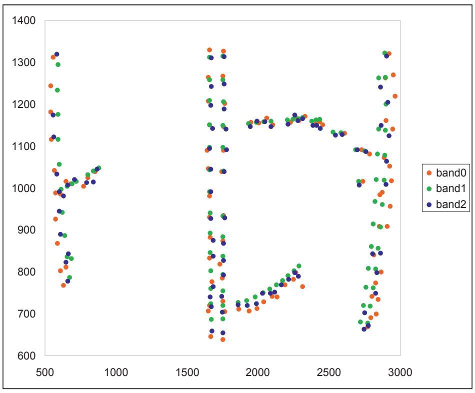

Fig. 8: Centroid point measurement; shift relative to green band1 is enlarged with a factor 100.

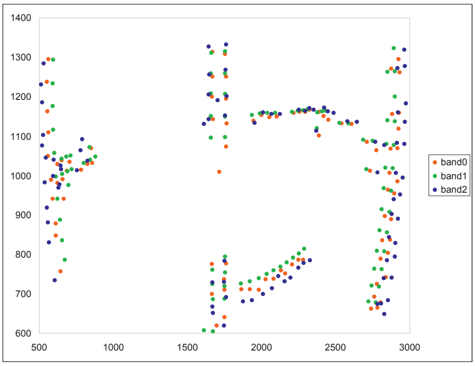

Fig. 9: Weighted centroid point measurement; shift relative to green band 1 is enlarged with a factor 100.

Fig. 10: Part of a spherical panorama after merging three colour bands processed with colour specific calibration parameters.

Tab. 2: Differences between colour bands for the two measurement methods.

Coluor bands		**Centroid** x, y (pixel)	**Weighted Centroid** x, y (pixel)
Red – Green	RMS	0.31, 0.15	0.23, 0.16
	min.	−0.51, −0.49	−0.52, −0.87
	max.	0.64, 0.21	0.57, 0.15
	Δf (pix/rad)	+0.30	+0.20
Blue – Green	RMS	0.13, 0.10	0.53, 0.24
	min.	−0.32, −0.38	−1.08, −0.75
	max.	0.24, 0.24	0.79, 0.93
	Δf (pix/rad)	+0.03	+0.52

92 targets are shown in the figures below and the statistics in the change in focal length is computed with the lens distortion parameters fixed. The values used were estimated using the green band. It clearly shows the image magnification of the red and blue bands relative to green; at an angle of 90 degree between optical axis and incoming ray the largest mean shift is 0.82 pixel $(0.52 \cdot \pi/2)$ found with the weighted centroid method in the blue band.

Six sets of camera parameters (one for each combination of three colours and two measurement methods) were estimated with CycloMedia's adjustment software. The estimated standard deviation was close to 0.16 pixel for all adjustments. For each measurement method the RGB images were resampled to a spherical panorama, each with its own set of camera parameters. An example (based on the weighted centroid method) is shown in Fig. 10.

Comparison with a spherical panorama computed using a single set of calibration parameters based on the green band did not show any significant improvement. This is not surprising because the corrections applied are at the sub-pixel level, while the most visible colour aberration, i. e. the surplus of red in the black target (see Fig. 7),

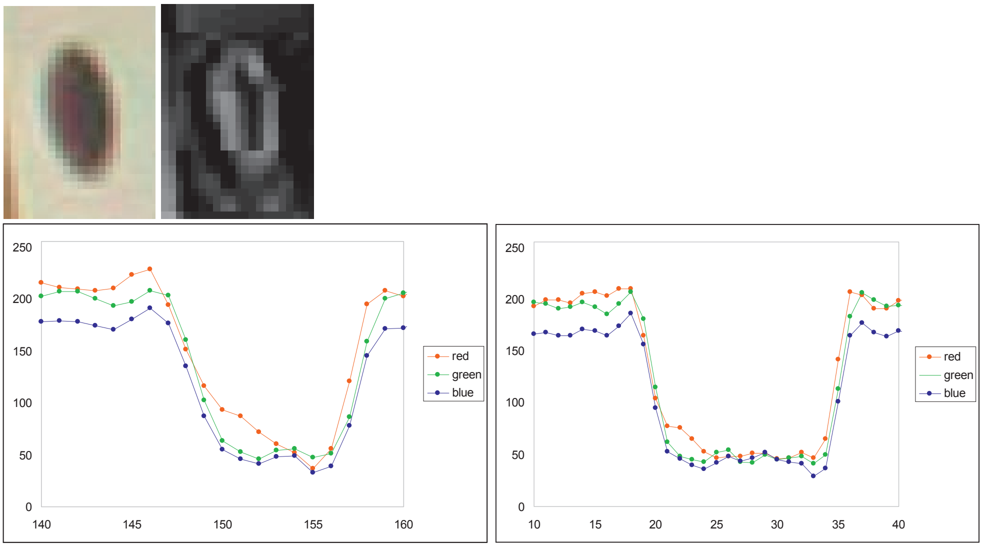

Fig. 11: Sample target (Fig. 7), top-left: after manual correction of chromatic aberration, top-right: red minus green band (stretched), bottom: RGB profile in column direction of a small and a large target.

spreads over 5 to 6 pixels in radial direction. This leads to the conclusion that for the visible colour aberration for the images under consideration, lateral chromatic aberration plays only a minor role.

3.4 *Manual reduction of chromatic aberration*

The question arises what causes the colour aberration apparent in Fig. 7. No scientific literature on the subject could be found, however, on the Internet a type of colour aberration called "purple fringing" is discussed (Wikipedia 2006). There is no agreement on the exact cause, but this colour aberration is frequently found in digital photography, especially with wide angle lenses, at large apertures, in the corners of the image (radial aberration), and in high contrast areas. Several image processing packages allow to manually correct for chromatic aberration. Commonly these packages allow to manually set a magnification for the red and blue colour band in order to improve the fit with the unaltered green band. We have tested Picture Window Pro 4.0. The results on the targets of Fig. 7 are shown in Fig. 11.

A significant visual improvement has been obtained. However, from Fig. 11 it is clear that this does not fully correct the aberration. For a final solution more research into the nature of the problem is required.

4 Conclusions

The paper presents the camera calibration procedure developed by CycloMedia that ensures the geometric quality of her spherical panoramas called Cycloramas. The least-squares adjustment involved in the calibration shows the semi-automatic target measurement to be accurate to the sub-pixel level with 0.24 pixel estimated standard deviation. This implies that the angular precision of well identifiable targets measured in a Cyclorama is 0.018° or 3 mm at 10 m.

The calibration procedure has been applied for an estimation of a set of interior orientation parameters per colour band aiming at elimination of lateral chromatic aberration, firstly to improve the imagery visually, and secondly for improving the potential measurement precision. This approach was not successful because the corrections found were below one pixel while the visible chromatic aberration stretches over more than 5 pixels. With adjusting the magnification of the red and blue band manually it was possible to improve the visual appearance of the imagery significantly, however, more research is needed into the nature of the problem in order to develop a final and automated solution.

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