OBJECT BASED DETERMINATION OF COMPARATOR COORDINATES IN BLURRED IMAGES

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Abstract :

A method for the determination of 2D comparator coordinates in blurred images for orientation and photogrammetric point determination purposes is described. From a certain amount of image blur it provides an accuracy enhancement compared to visual or edge based digital measurement. Homologous image points are defined based on geometric optical laws. The method is applied to images blurred by an inproper arrangement of the optical components between object and image surface; it may be extended to images blurred by any physical reason. The results obtained by processing a 3D-point determination for a multi-media image block prove the practicability of this method.

KEY WORDS : Comparator Coordinates, Blurred Images, Ray Tracing, Target Matching, Bundle Adjustment

1.Occurance of Blurred Images

A blurred image is the result of disturbed optical imaging and can be caused by several physical effects:

- by relative movement between camera and object; this is mainly a problem of aerial photogrammetry
- by a reduced resolution of the image sensor; this can be noticed very well on colour sensitive CCD cameras
- by an inproper arrangement of the optical components.
- by many other reasons, e.g. specific characteristics of films emulsions, film processing or light scattering between object and camera (see *Kupfer 1972* and *Mertens* 1980).

This paper deals with the case of inproperly arranged optical components, which means, that the relative spatial positions of camera and object are not well adjusted to the refraction properties of the media between image plane and object . This leads to:

1. Unsharpness, caused by geometric optical aberrations of rays.

2. Variations of the distortion within the small image of the point target. In the context of this paper distortion means any shift of an image point within the image plane from the position resulting from a pure central perspective transformation to another position by any physical reason.

3. Unsharpness, caused by diffraction.

This paper deals with unsharpness as stated in point 1. and distortion variations, as stated in point 2. Only these two effects are called aberrations in this context. Note this definition of "aberrations" differs from that used in optical science, where not only distortion variations, but distortions themselves are defined as aberrations, too. But these do not affect the measurement of comparator coordinates. See Fig. 1 as an example for geometric optical aberrations: the target on the left side is imaged to a blurred target image, to be seen on the rigth side.

The diffraction, named under 3. is not included for reasons described later in section 2.2.

The problem of inproper arranged optical components is typical for a wide range of close range applications. For example:

- A certain depth of field, required due to network optimization, can overtax the optical capabilities of the used camera.

- In the extreme close range there is no depth of field; unsharp images can only be avoided if the object is completely flat and the camera fulfills the Scheimpflug-condition.

- In multi-media applications further optical components, i.e. refracting surfaces and refraction indices of media, are added to the space between object and camera (Fig. 2). In general, this leads to reduced image quality, because the blur minimization of a standard lens design is valid only if one specific medium is located between lens and object.

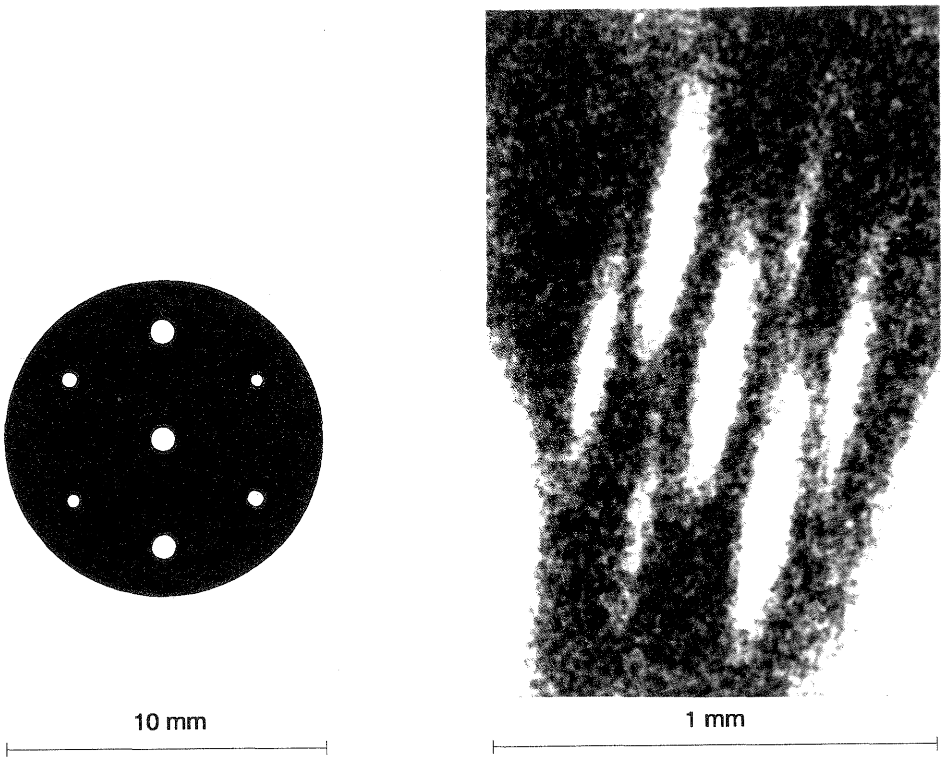

Fig. 1: imaging of a target (left side) to a target image (right side) blurred by geometric optical aberrations

In multi-media photogrammetry a minimization of blur for a special project by optical design considering the additional media is possible. But this is only realistic, if the arrangement of all optical components - camera and additional media - is constant for each exposure of the project. This case is called bundle invariant (*Kotowski 1988*). An example for a bundle invariant multi-media application is the underwater photogrammetry with cameras emedded and fixed in watertight and pressure-resistant housings.

If the shape and positions of the refracting surfaces between camera and object are constant in relation to the object, an image blur minimization is impossible. Exposures of an object placed behind a glass plate taken with convergent optical axes may serve as an example for this case of an object invariant image block.

To avoid a major accuracy reduction in those images the extension of classical comparator measurement methods to an object based method is presented.

2.Principles of Determining Comparator Coordinates

The determination of comparator coordinates can be devided into two steps: the definition of image points and their identification.

2.1.Classical Measurement in Images of Sufficient Sharpness

The classical methods of determining comparator coordinates, visual measurement and edge based digital measurement define image points geometrically: the center of an object target, defined as the object point, is assumed to be imaged as the center of density of the sufficiently sharply contured target image, because the basic imaging model used in photogrammetry is central perspective, possibly disturbed by distortion only. Object- and image point correspond by the perspective ray. So, the target image center is defined as the image point.

In geometrical optics the principle ray is equivalent to the central perspective ray. This ray can be assumed to be identical for all wavelenghtes, if the imaging is sufficiently perfect (*Hofmann 1980, pp.91f*). Only in this case the just given image point definition makes sure, that the center of the target image is identical with the intersection point of the principle ray with the image plane.

2.2.Extension to Object Based Determination

If the aberrations are increased by an inproper arrangement of the optical components, the principle rays of different wavelengthes now diverge; so their

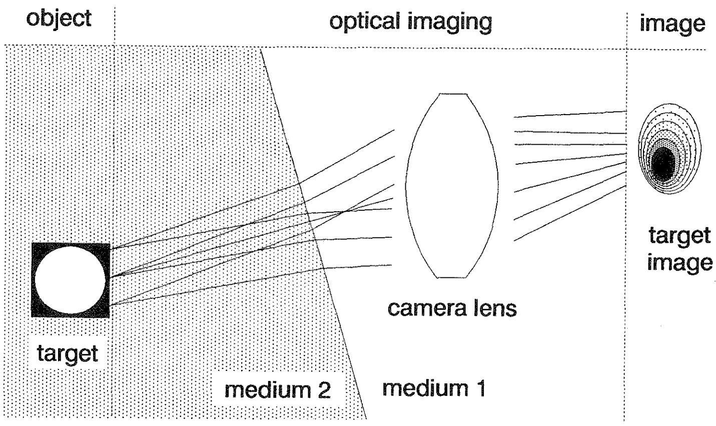

Fig. 2: geometric optical imaging, causing aberrations because of an additional medium between camera and object

intersection points with the image plane are distributed within the target image. This causes two effects on the image point definition:

1) An unambiguously corresponding ray does not exist any more. For that reason in blurred images the corresponding ray is now to be defined as the principle ray of one specific wavelength and the image point as its intersection point with the image plane. The wavelength can be selected arbitrarily from all the wavelengthes passed through the optical system, but, to achieve an homologous definition, it has to be constant for all points in one image block.

2) Generally, the center of density of the target image is neither identical to one of the principle ray intersection points nor does it belong to the equivalent imaging ray regarding several object targets, because the distribution of all ray intersection points is nonsymmetric and differs for each target image (*Kingslake 1965, pp.212f*).

Moreover, because of the unsharpness the identification of any defined image point is more difficult. Consequently, both steps of comparator coordinate determination, point definition and identification are affected.

Based on the image point definition given under 1), in a blurred target image the image point must be identified within an infinite number of principle ray intersection points. Since these intersection points are not separately visible and the visual shape of the target image does not allow a trivial identification of one special intersection point, as it is possible in sharp images by identifying a target center, the knowledge about the target image formation has to be included into the image point identification. Based on geometric optical laws, a representative number of imaging rays starting from the object target can be traced through the complete optical system, if the spatial arrangement of object points, optical system components and image plane as well as the shape of the object targets that represent the object points are known (see Fig. 2). The distribution of the resulting intersection points in the image plane create a density model of the target image, furthermore called target image model. Each of the traced rays belongs to one intersection point, so that selected rays, e.g. the principle ray of one specific wavelength, defined above as the corresponding ray, can be identified within the target image model. To transfer this image point into the real target image, the density distribution of the target image model is transformed into a digital image and this digital image afterwards matched with the real, digitized target image (see details in section 3.2.). To call the method object based originates from the access to information about the object target shape.

The computation of the target image models takes the aberrations named under 1. and 2. into account. Furthermore, the trayced rays ar weighted dependent on their wavelengthes; these weights result from the spectral characteristics of the illumination, the target remission, the transparency of the optical system and the sensor surface (e.g. film emulsion). The influence of diffraction, named under 3., is not considered, because its meaning decreases, when the geometric optical aberrations increase (compare *Cox 1964, p.373, Kraus 1982, p.58, Marchesi 1983, p.26, Myamoto 1961, p.58*). In a first development step, the concept of the method is designed for artificial targets of given size and shape.

3.Description of the Complete Process

Fig. 3 shows the flow of the object based determination of comparator coordinates and its interdependency with the orientation. This section describes the process in detail, Section 3.1 the definition of the image points, 3.2 their identification.

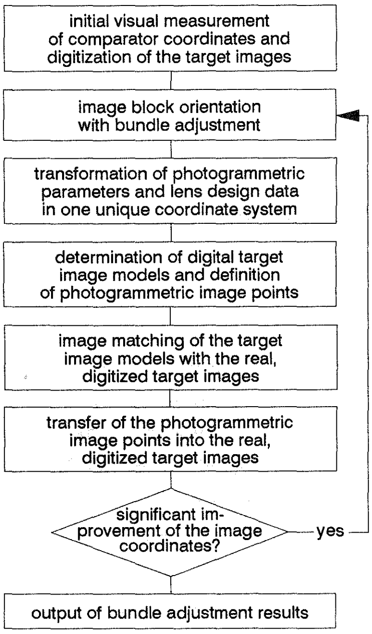

Fig. 3: flow of the object based comparator coordinate determination

3.1.Definition of Image Points

3.1.1. Initial Visual Measurement of Comparator Coordinates and Digitization of the Target Images

In this first step initial values for the comparator coordinates of all target images of the complete image block are measured visually and the target images are digitized simultaneously with the measurement.

3.1.2. Image Block Orientation by Bundle Adjustment

The second step is an initial orientation of the image block, that means, the coordinates of the object points, the parameters of additional refracting surfaces, the exterior and interior orientation parameters are estimated simultaneously by bundle adjustment (*Kotowski 1988, pp.328ff*). Since the comparator coordinates are not yet sufficient, the results are not final. But, this initial orientation is required, because the outcoming parameters are to be used in the following steps to compute the target image model. So, the whole process is iterative.

3.1.3. Transformation of Object Points and Parameters of Additional Refracting Surfaces into a Geometric Optical Coordinate System

To compute the target image models the coordinates of the object points, the parameters of the additional refracting surfaces and the design components of the camera lens must be available for each image in one unique coordinate system. For this purpose a geometric optical coordinate system, typically used in optical design, is suitable. One of its axes is collinear with the optical axis; its origin may be fixed in the entrance pupil (compare *Meid, p.14*).

First the object points and parameters of additional refracting surfaces are transformed into the photogrammetric image coordinate system, which is fixed in the projection center, using the parameters of the exterior orientation. The photogrammetric image coordinate system differs from the geometric optical one, if

1. the optical axis is not perpendicular to the image plane,

2. the entrance pupil has another distance to the image plane,

3. the distortion is not radial-symmetric.

The transformation between the two systems has to be performed using their relationship to the image plane, because only the image plane is a physical part of the camera that is common to both. The transformation equations for the object points are as follows:

$$\mathbf{P}^{EP} = \mathbf{R}_{ij}(\mathbf{P}^* - \mathbf{a} - \mathbf{b} - \mathbf{dH} + \mathbf{c})$$

with

$\mathbf{P}^{EP}$	transformed object point in the geometric optical system
$\mathbf{R}_{ij}$	rotation matrix, rotating the photogrammetric system into the geometric optical system;
$\mathbf{P}^*$	object point, defined in the photogrammetric system
$\mathbf{a}$	vector, connecting entrance and exit pupil;
$\mathbf{b}$	vector, connecting exit pupil and principle point of collimation;
$\mathbf{dh}$	vector, connecting principle point of collimation and principle point;
$\mathbf{c}$	principle distance of the camera.

All data to solve this three dimensional vector equation can be taken from the reports describing the optical design and the camera calibration, respectively. The equation is identical for the transformation of the parameters of additional refracting surfaces, if these are defined in a vector oriented form.

3.1.4. Computation of Target Image Models and Definition of the Photogrammetric Image Points

Two conditions must be fulfilled by the mathematical models of the target images: they must allow the identification of the intersection points of the corresponding rays and they have to be realistic models of the density distribution in the real target image.

Using ray tracing for the computation of the target image models fulfills the first condition: Starting at an object target a representative number of rays is traced numerically through the optical system and intersected with the image plane (*see in detail Kotowski 1988 pp.324ff and Pegis 1961, pp.8f*). The type of each ray is defined in advance. This means, each of the traced ray is either a principle, a meridional, a sagittal or a skew ray, it starts with a certain incident angle from the object target and has one specific wavelength. One of these rays, the principle ray of one colour, is defined as the corresponding ray between object point and image point. The intersection of this ray as well as of all other rays results in a two dimensional distribution of intersection points, the first state of the target image model. The intersection point of the corresponding ray, well defined in this model, is defined as the photogrammetric image point.

If the density distribution of all intersection points in a target image model is equivalent to the density distribution of the real target image, the second condition is fulfilled. To achieve this representative distribution, the correct selection of rays to be traced is essential. Their number and their spatial distribution have to approximate the radiation that is sent back from the object target and darks the sensor surface sufficiently.

The abstraction from the radiation to be modelled to the distribution of discrete rays is processed in three steps. In the first step only that cone of radiation is modelled, that is assigned to only one wavelength and starts only from the center of the object target. The resulting intersection points in the image plane are equivalent to the point spread function, proposed in this shape by Herzberger (*Herzberger 1947, 1954, 1957*), called a spotdiagram. To achieve a realistic distribution of the rays one of the pupils is divided into surface elements of equal size and each ray is assigned to one of these pupil elements (*Herzberger 1958, p.106* und *Cox 1964 p.378*).

In the second step the object target itself is divided into small surface elements, which are of equal size, if a constant radiation can be assumed over the whole object target. Starting at the center of each of these surface elements, one spotdiagram is computed, leading to a group of overlapping spotdiagrams in the image plane. This distribution of intersection points, accumulated for one wavelength, shall be called the monochromatic target image model.

In the third step the whole spectrum of wavelengthes passing the optical system is divided into constant intervals. For each of the resulting wavelengthes the monochromatic target image model is computed as described in the previous paragraph. The spectral characteristics of the illumination, the target radiation, the transparency of the optical system and the sensor surface have to be considered by introducing an adequate weight for the rays of each of the several wavelengthes.

So, the required ray tracing for the computation of a target image model is complete. The three accumulated varieties of intersection points are overlayed by a raster with a raster field size equivalent to the pixel size of the real digitized target image. The intersection points are counted in each field separate and the number of points in one field is interpreted as a density value, resulting in a digital image with a certain density characteristic.

To represent the density characteristic within the target image realistically, the number of traced rays must be large enough. To prove this the difference between the density values derived from two intensifications of numbers of traced rays is computed: If this difference is still significant, a further intensification has to be performed, i.e. more rays have to be traced, as long as the density characteristic does not change any more.

As mentioned above, for each target the principle ray of a constant wavelength, starting from the object target center, is defined as the corresponding ray and its intersection point with the image plane is the photogrammetric image point. Its position within the digital target image model is known; to identify it in the real target image, it has to be transferred there.

3.2. Identification of Comparator Coordinates for the Defined Image Points

To be able to identify the photogrammetric image points in the real target image, this and the digital target image model have to be matched, e.g. by least

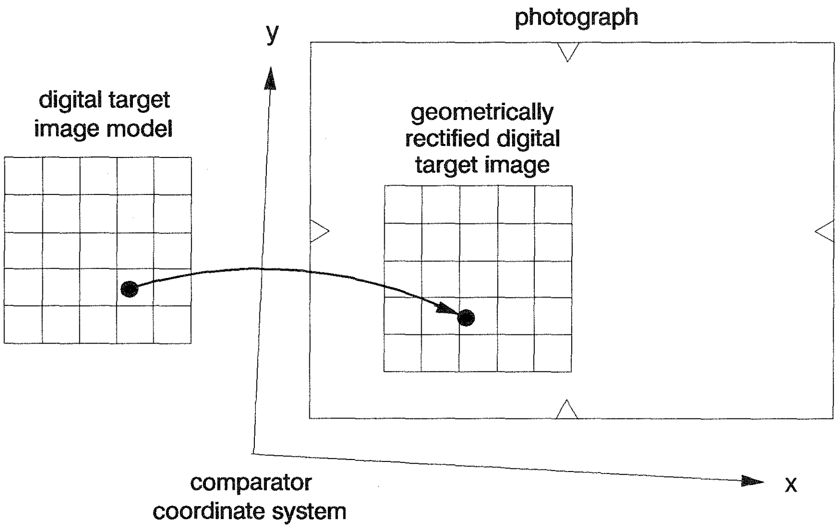

Fig. 4: matching of a digital target image model with a digitized target image and transformation of a photogrammetric image point defined in the target image model

square matching.

Both digital images are of the same geometric shape, because the target image model is computed in a metric coordinate system and the digitized target image is geometrically rectified by the transformation into the comparator system. The way this transformation can be performed depends on the type of the comparator. If, for example, the comparator is equipped with a reseau, the digitized target image is transformed into the comparator system by using the imaged reseau crosses. After eliminating a possible rotation parameter between the photograph and the comparator system the geometric parameters of the image matching consist only of two shifts.

The radiometric parameters of the matching have to describe a linear transformation between both digital images, because from the ray tracing procedure only relative density information can be derived, level and scale are not achieved. Therefore the target image model has to be adapted radiometrically to the target image. Dependent on the density characteristic of the photograph, in some cases disturbing pixels around the edge of the target image model have to be eliminated before the matching (see *Meid, pp.48ff*).

Using the outcoming matching parameters between both digital images the photogrammetric image point can be transformed into the real, digitized target image. With the transformation parameters between the digitized target image and the comparator coordinate system the point can finally be transformed into the last-mentioned one (Fig. 4).

If this is done for each point of the complete image block, one iteration for the determination of comparator coordinates is complete.

3.3.Orientation with Improved Comparator Coordinates

If the accuracy of the bundle adjustment can be increased by introducing the image coordinates derived from the new comparator coordinates, the efficiency of the method is proved. Further iterations of the whole process (see Fig. 3) have to be performed as long as the accuracy of the bundle adjustment increases.

4.Test of the Method on the Basis of an Example

In this section the results of an underwater photogrammetry project are presented. An orientation of three underwater images on 28 object targets (see the arrangement in Fig. 5, and see one of the targets in Fig. 1 on the left side), fixed at a frame, was required. The used camera was embedded in a housing, directed to a plane-parallel housing window with a thickness of 2.5 cm. This caused a dramatic decreasing of the image sharpness from the center of the photographs to the rims (see also *Przybilla et. al. 1988*). Fig. 1 on the rigth side shows one of the blurred target images.

To demonstrate the results of the orientation by bundle adjustment, the residuals of a visual measurement and of an object based determination are compared (Fig. 6). The best visual measurement of three different persons led to the residuals shown in Fig. 6

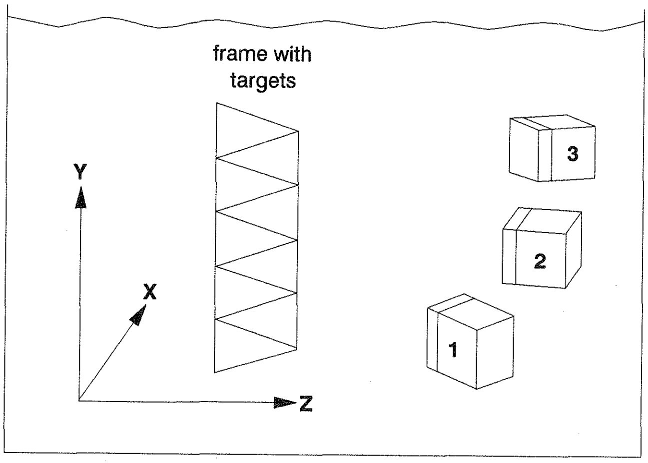

Fig. 5: underwater photogrammetry project

on the left side for the middle image. The area within the dotted line will not be looked at, because the imaging quality in this center part of the photograph was very good, so that visual measurement and object based determination were not significantly different. The residual mean square value of the points outside this area was ± 11.7 μm. The coordinates visually measured were introduced into the object based determination as initial values; in the course of the determination the visually measured points were shifted for a distance of 6.8 μm (mean value). After the orientation with the improved image comparator coordinates the residual mean square value was decreased to ± 7.6 μm. The network design of both compared adjustments was the same, of course.

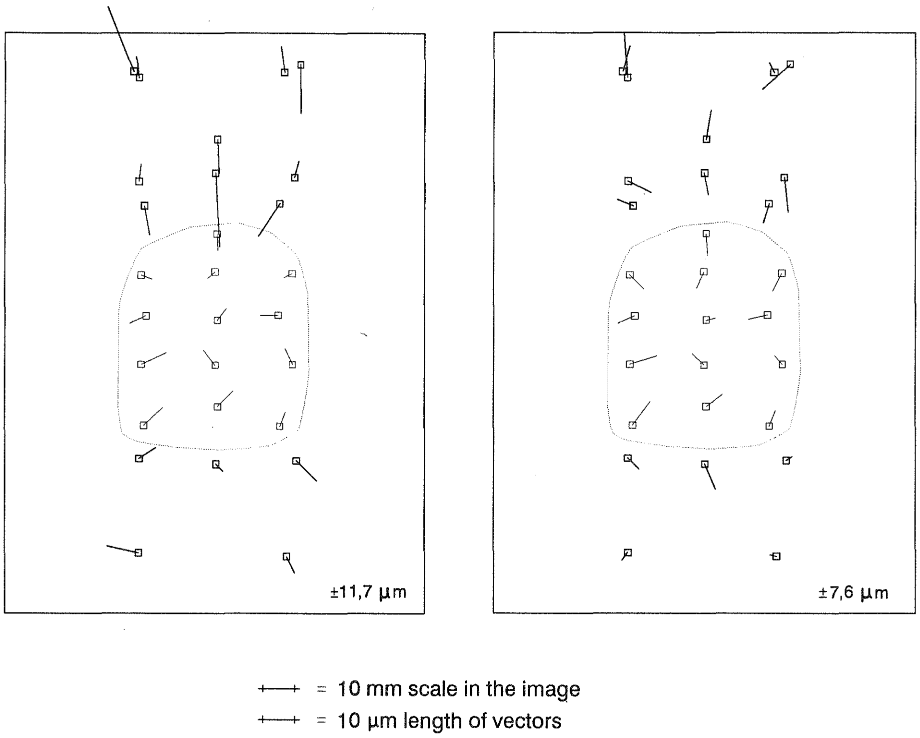

Fig. 6: residuals after bundle adjustment at visually measured points (left side) and at object based determined points (right side)

5.Conclusion

The described object based determination of comparator coordinates is a method for determining homologous image points in blurred images. It differs from visual or edge based digital measurements by defining and identifying the image points using the imaging model of geometrical optics. An example for the improvement of visually measured comparator coordinates by this method could be demonstrated.

Compared to classical photogrammetric measurements, the object based determination needs additional information: size and shape of the object targets and the spectral characteristics of all imaging components between object and image plane. Furthermore, the design data of the optical system must be given. These data normally cannot be accessed, because the manufacturers keep them confidential. Nevertheless, to obtain the spotdiagrams the manufacturers themselves could perform the ray tracing computations.

The principle of the object based determination is not restricted to multi-media photogrammetry; it can be extended to any application, where images are blurred by known physical effects.

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