GEOMETRIC ACCURACY POTENTIAL OF THE DIGITAL MODULAR CAMERA

Liang Tang[1], Christoph Dörstel[2], Karsten Jacobsen[3], Christian Heipke[3], Alexander Hinz[2]

[1] Techedge GmbH Consulting & Software, Kirchheim/Munich, tang@techedge.de
[2] Z/I Imaging GmbH, Oberkochen, doerstel@ziimaging.de
[3] Institute for Photogrammetry and Engineering Surveys, University of Hanover, jacobsen@ipi.uni-hannover.de

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ABSTRACT

The Digital Modular Camera (DMC) is the new digital aerial camera system of Z/I Imaging. It is based on CCD areal array sensor technology and provides a very high interior geometric stability. According to its modular design, more than one individual camera module can be tied together, resulting in a large field of view of the camera. The DMC high end configuration consists of four panchromatic and multi-spectral modules, respectively. The four panchromatic modules are arranged in a matrix, two across track and two along track and have their optical axes looking downwards in a slightly divergent set-up so as to reach a large ground coverage. A post-processing procedure serves to transform the four individual images into one virtual image which can be considered being of a normal central projection. The multi-spectral modules are arranged around the panchromatic modules acquiring nadir looking views. Their imagery has the same ground coverage as that of the virtual image but a reduced resolution.

The paper deals with the geometric accuracy potential of the DMC from the photogrammetric point of view. The system structure is outlined. Factors which influence the mapping accuracy are analysed and discussed. An outlook on future applications concludes the paper.

1   INTRODUCTION

In the modern photogrammetric processing chain the aerial film camera is the only remaining analogue component in an otherwise completely digital range of products. With the development of the Digital Modular Camera (DMC) announced in September 1999 (Hinz 1999), Z/I Imaging is going to close this gap and will offer an end-to-end digital product line for photogrammetric and geo-engineering applications. Because of its modular design that components can be changed and upgraded without having to change the whole camera system, the DMC can take full advantage of new developments in sensor, computer and mass storage technologies.

With the DMC development, the existing aerial cameras will not suddenly become obsolete, however. They will remain to have their share of the market. Nevertheless, the DMC already has a large number of applications. For example 3D city model generation and update, disaster monitoring and documentation, infrastructure mapping and precision farming to mention just a few. For these applications the inherent geometric stability of the DMC, the superior radiometric image quality as compared to film because of a higher dynamic range of the employed CCDs, the possibility to simultaneously acquire panchromatic and multi-spectral imagery, the quick availability of the image data, and last not least the fact that chemical processing of the films in the photo lab is not necessary any more, are the main advantages of the DMC.

The simultaneous image acquisition in multiple spectral bands shows that besides being a sensor for traditional photogrammetric work, the DMC is also a remote sensing instrument, exemplifying the merge between photogrammetry and remote sensing which has taken place in the last decades. This fact raises the question of a possible competition between aerial cameras such as the DMC and space sensors, e. g. Space Imaging´s Ikonos II with 0.8m GSD (Ground Sampling Distances) in panchromatic and 3.2m GSD in multi-spectral mode. Without exploring this issue more detailed in this paper – answers will depend on data availability due to meteorological reasons (e.g. clouds), turn-around times, costs, and other non-technical issues (see Heier 1999 for a related market study) – it is pointed out here that digital aerial cameras are certainly more flexible and thus can be used at shorter notice.

It is worth mentioning that not only Z/I Imaging but also LH Systems is developing an all-digital airborne sensor for photogrammetric and remote sensing applications, the ADS (Airborne Digital Sensor, Fricker et al. 1999). While DMC is based on CCD areal array technology, ADS is a linear array scanner operating according to the 3-line principle (Hofmann et al. 1984). Both approaches have been shown to be applicable in principle to photogrammetric work in the past (see e. g. Thom, Jurvillier 1993; Toth 1997 for CCD arrays and Hofmann et al. 1993; Heipke et al. 1996; Wewel et al. 1998; Neukum 1999 for CCD line sensors).

Significant advantages of the DMC as compared to line sensor cameras stem from the fact that the DMC delivers central projection image. Therefore, DMC images are compatible with existing software in Digital Photogrammetric Workstations (DPWS), no camera-specific software adaptations are required. Functions and procedures within the photogrammetric processing chain which are used to process digital images obtained by scanning aerial photographs can be applied directly to the DMC images. A second advantage is that the DMC images can be oriented in much the same way as conventional aerial photographs, without any additional measurements for the exterior orientation parameters, i. e. from GPS/INS. While GPS/INS enhances the applicability and productivity of any camera system, GPS signals are, however, not always available with high precision, the combined processing of GPS/INS and image data requires additional calibration efforts, and is therefore complex and error prone. Thus, the fact that the DMC does not rely on these additional sensors must be seen as a clear advantage over those line sensor cameras which require GPS/INS measurements for further processing. Other advantages of CCD areal array cameras include the possibility to introduce forward motion compensation via TDI (time delayed integration; see Thom, Jurviller 1997), and the fact that independent of flying height and speed the GSD of a DMC image is always quadratic.

This paper deals with the geometric accuracy potential of the DMC from the photogrammetric point of view. In the next chapter the DMC itself is described, before the geometric processing of the DMC imagery is explained and factors which influence the mapping accuracy are analysed and discussed in detail. An outlook on future applications concludes the paper. Comprehensive descriptions on the DMC project can be found in (Hinz, Dörstel, Heier 2000 and Diener, Kiefner, Dörstel 2000).

2   THE DIGITAL MODULAR CAMERA

The DMC is based on CCD areal array technology. Ideally, a single CCD chip similar in size and resolution to the existing film cameras, and thus providing high geometric accuracy in conjunction with superior radiometry, should be used. However, today such a large-format chip is not available yet for technological and economical reasons. Nevertheless, a large field of view is mandatory in aerial photogrammetry due to the high accuracy requirements and the economical fact to reduce the number of strips which have to be acquired and thus the flying time for a given project. In order to meet these demands the DMC consists of a set of single CCD chip camera modules operated parallel to each other. The high resolution DMC configuration is composed of four panchromatic and up to four multi-spectral modules, respectively (see Fig. 1). The four panchromatic modules are arranged like a 2×2 matrix and have their optical axes looking downwards in a slightly divergent set-up so as to reach a large ground coverage. A post-processing procedure serves to transform the four individual images (called sub-images) into one virtual image which can be considered being of a normal central projection (see Fig. 2). The multi-spectral modules are arranged around the panchromatic modules and acquire nadir looking views. The multi-spectral imagery has the same ground coverage as that of virtual image but a reduced resolution.
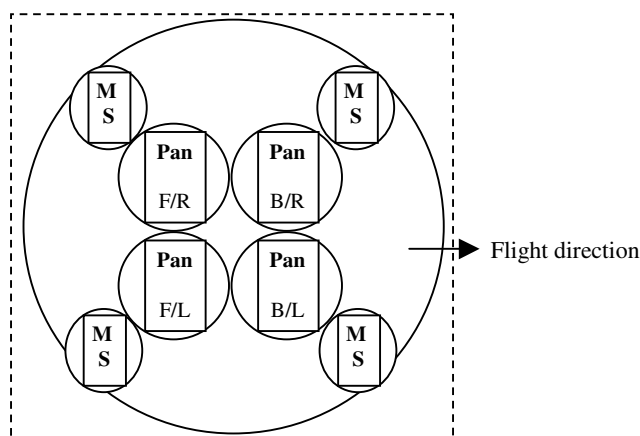

Fig. 1.   DMC standard constellation with four panchromatic (Pan) and multi-spectral (MS) modules, where
F/R = forward right looking (facing flight direction)
B/R = backward right looking
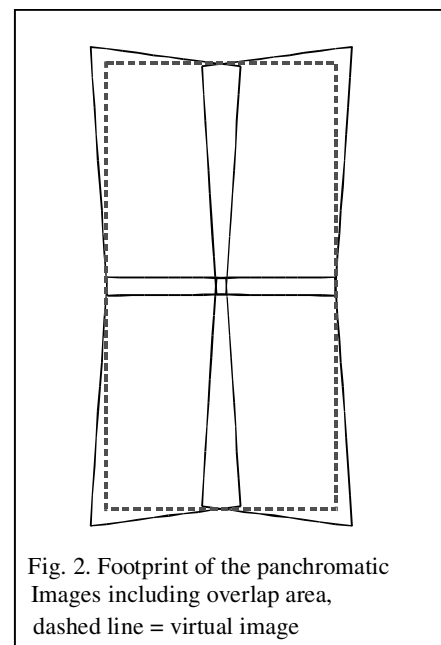F/L = forward left looking
B/L = backward left looking.

Fig. 2. Footprint of the panchromatic Images including overlap area, dashed line = virtual image

Since further discussions will be devoted to geometric issues of the DMC, properties of panchromatic modules will be described in the following only. Table 1 summarises some technical data and parameters of the high resolution DMC

configuration which is investigated in this paper. Due to the CCD architecture, the short chip side (image rows) has to be arranged along the flight direction, i.e. the x-axis of the camera coordinate system. Tilt angles of individual modules result in an overlap of about 1% between the sub-images. A solid cast frame guarantees the stable geometric relationships between individual modules. Like the frame film camera, forward motion compensation (FMC) is introduced to each camera module. TDI (time delayed integration) techniques serve to accomplish the task (cf. Thom, Jurviller 1997).

Parameter	Value
Assembly:	
approx. distances between lenses in *x* and *y* (‖row/column) [mm]	80/170
app. tilt angles φ/ω (‖row/column)	10°/20°
Module/Sub-image:	
Calibrated focal length c_{sub} [mm]	120
Pixel size pel_{sub} [µm]	12
Radiometric resolution [bit]	12
Image size [Pixel]	4096×7168
Image size [mm]	49.15×86.02
approx. field of view (‖row/column)	23°/39°
Virtual image:	
Defined focal length c_{virt} [mm]	120
Pixel size pel_{virt} [µm]	12
approx. image size [Pixel]	8000×14000
approx. image size [mm]	95×168
approx. field of view (‖row/column)	44°/74°

Table 1. Technical data and parameters of the DMC constellation (panchromatic only) investigated in this paper. The row direction points in, the column direction perpendicular to the flight direction.

3   GEOMETRIC SITUATION OF THE DMC

As mentioned before, sub-images are transformed to generate a so-called virtual image prior to further processing. For mapping purposes the accuracy of the virtual image comes of course first of all into question. Two main issues are of interest, i.e. the transformation influence within a virtual image and the possible point displacement during stereo processing.

3.1   Accuracy aspects of the DMC virtual image

3.1.1. The transformation influence. In order to be able to use existing standard photogrammetric software for subsequent processing tasks, it is mandatory to model the virtual image as a single central perspective image. For the high resolution DMC configuration mentioned in chapter 2 this means that we should summarise the four individual projection centres into one. This kind of transformation can be formulated as a general case of eccentric central projection, which is a function of both the camera orientation and the object surface undulation. Thus, the rigorous way to transform the sub-images into the common image plane of the virtual image is to go via object space, i.e. using a digital terrain model (DTM) which is, however, not available in general. Therefore, a two-dimensional transformation must be used to approximate the rigorous solution. Obviously, in this way a geometric displacement is introduced due to the different projection centres, if the terrain is not flat.

To avoid the complexity to derive the rigorous formula according to the transformations via object space we choose in the following a more intuitive, geometric approach to analyse this influence based on the parameters in table 1. It should be noted that in order to use the displacement values given in this table the four sub-images must be acquired at exactly

the same moment in time. This condition can be fulfilled by proper time synchronisation. Also, the relative orientation of the individual cameras can be treated to be stable over time.

In Fig. 3 two sub-image planes are shown together with the one of the virtual image. With reference to this figure we first select a flying height h_g above a horizontal reference plane in object space for which the geometric influence can be made to vanish. The point Q is located at such a position on the reference plane that it is imaged into the principal point of the virtual image. Thus Q'_{virt} separates the contributions of two neighbouring sub-images to the virtual image. Next, the point P is placed at a height of Δh above the reference plane such that $P'_{sub} = Q'_{sub}$. Due to the height difference Δh and the offset of projection centres dX_0 the two mapped points P'_{virt} and Q'_{virt} in the virtual image become different. The displacement dX in object space can be formulated as follows for the X and Y- directions:

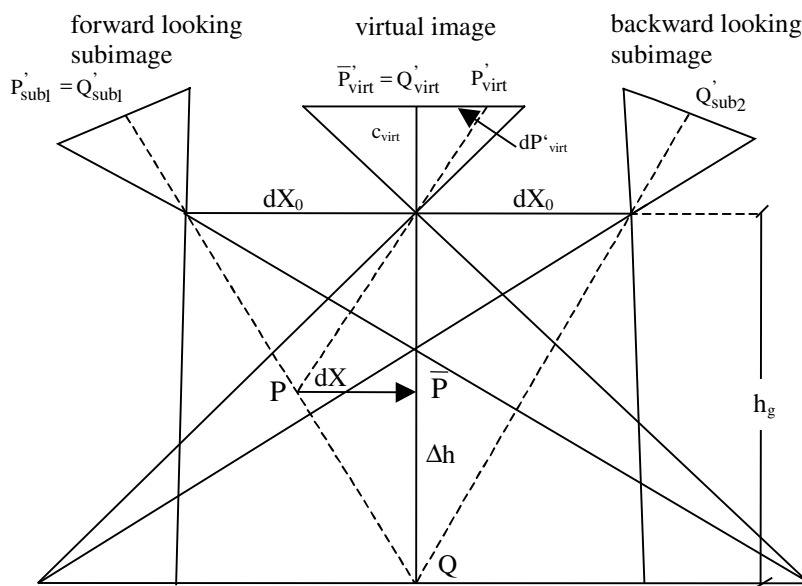$$dX = \frac{\Delta h}{h_g} dX_0 \ , \qquad dY = \frac{\Delta h}{h_g} dY_0 \tag{1}$$

Fig. 3. Geometric relations of the DMC in flight direction

Thus, the corresponding coordinate corrections of P in image space can be computed by

$$dx' = \frac{c_{virt}}{h_g - \Delta h} dX = \frac{c_{virt}}{h_g} \frac{\Delta h / h_g}{(1 - \Delta h / h_g)} dX_0 \quad \text{and} \quad dy' = \frac{c_{virt}}{h_g} \frac{\Delta h / h_g}{(1 - \Delta h / h_g)} dY_0 \tag{2}$$

so that $\overline{P}'_{virt} = P'_{virt} - dP'_{virt} = Q'_{virt}$. Therefore, the values of dx' and dy' present the resulting transformation influence at the point P in the virtual image. The equations (1) and (2) are of course not only applicable to the special location of P but also to any arbitrary location above or below the reference plane. It should be noted that the overlap area between the forward and the backward looking sub-image in fig. 3 is exaggerated due to the largely exaggerated ratio dX_o / h_g. The actual overlap amounts to about only a few percent of the size of the sub-image.

3.1.2 The height displacement. The shift in the X-component has also an influence onto the Z-coordinate derived from stereoscopic measurements. Assuming the normal case with an end overlap of 60% the resulting model is based on the combination of a forward looking module of one 2×2 image set and a backward looking one of the following image set (see Fig. 4). For a point R at a height Δh above the reference plane in the centre of the model, the transformation influence in both virtual images can be computed according to equations (2). They are of the same absolute value but different signs. Therefore, the sum of the two absolute values can be considered a parallax displacement d_{px} of the stereoscopic measurement in the virtual images for determining the height of R. The resulting influence in height is

$$dZ = \frac{hg}{c_{virt}} \frac{hg}{B} d_{px} = \frac{hg}{c_{virt}} \frac{hg}{B} 2 \frac{c_{virt}}{hg} \frac{\Delta h / h_g}{(1 - \Delta h / h_g)} dX_o = \frac{c_{virt}}{b} \frac{\Delta h / h_g}{(1 - \Delta h / h_g)} dB \qquad (3)$$

where B and b stand for the stereo base in object and image space, respectively , and the base displacement $dB = 2 \times dX_0$. For some highly accurate applications the resulting height influence can be totally compensated by changing the virtual focal length by a value of dc_{virt} . Since $dZ/dc_{virt} = (h_g - \Delta h) / c_{virt}$ we have $dZ = (h_g - \Delta h) / c_{virt} \, dc_{virt}$ and can equate this expression with the one in equation (3), leading to

$$\frac{c_{virt}}{b} \frac{\Delta h / h_g}{(1 - \Delta h / h_g)} dB = \frac{h_g - \Delta h}{c_{virt}} dc_{virt} \qquad \text{thus} \qquad dc_{virt} = \frac{c_{virt}}{b} \frac{c_{virt}}{h_g} \frac{\Delta h / h_g}{(1 - \Delta h / h_g)^2} dB \qquad (4)$$
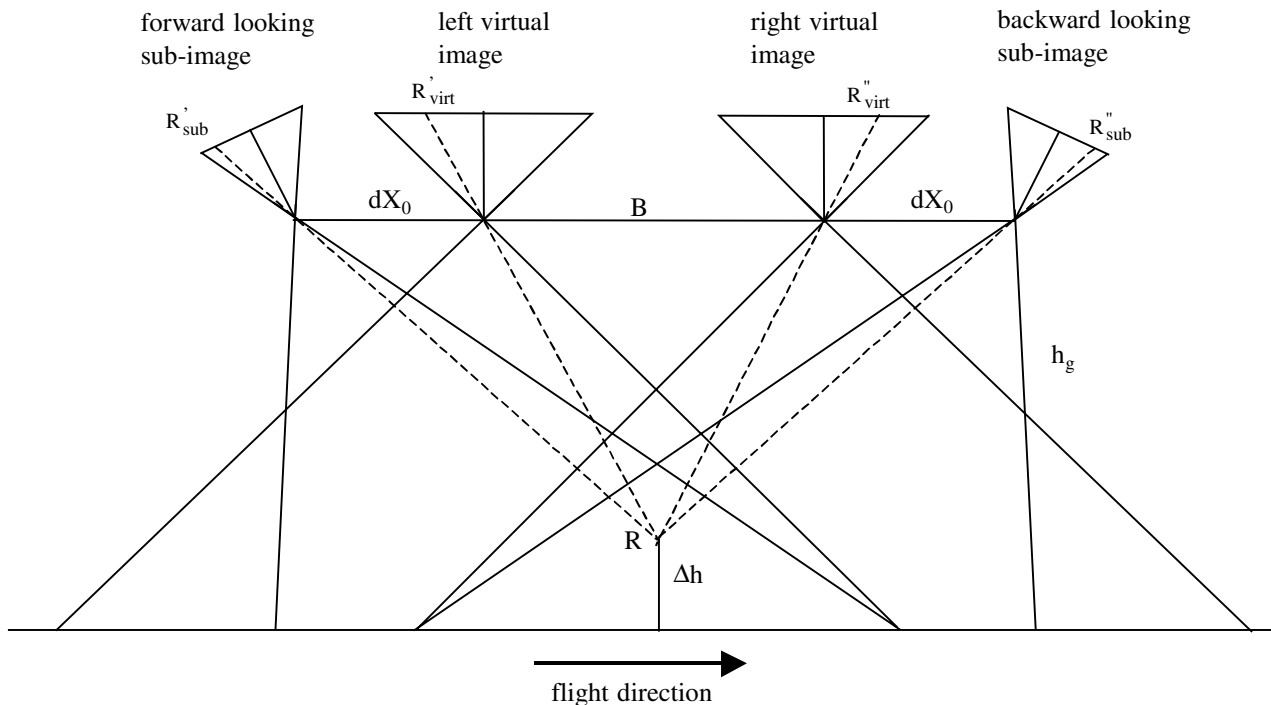

Fig. 4 : DMC stereo model and the height displacement

3.2 Applicability of the DMC

Fig. 5 shows the transformation influence caused by the ratio of $\Delta h / h_g$ for different flying heights. As can be seen, the dx' and dy' decrease by increasing the flying height, and its values are not very large even for small values of h_g. For the Y-component it could reach up to 0.43 pixel for a flying height of 500m and $\Delta h / h_g = 0.2$, what means a terrain height of 100m above or below the reference plane. This displacement corresponds to only 1.7 cm on the ground. The influence in X is even smaller due to the smaller displacement between the two projection centres along the flight direction. In practice, the ratio of $\Delta h / h_g$ only under extreme conditions exceeds the value of 0.2 since this already corresponds to a variation of the object height of 40% in relation to the flying height. Normally in such cases separate flight lines will be introduced.

The described influences in planimetry and in height can of course be completely circumvented by directly using the sub-images in the photogrammetric processing chain as opposed to using the virtual image. For sufficiently defined object points a resulting accuracy in the image of 0.3 pixel can be reached, even in a scanned film image. This limit could be exceeded by the Y-component if the flying height is lower than 500 m and the ratio of $\Delta h / h_g = 0.2$. As pointed out the effect on the Y-coordinate in this case is 1.7 cm on the ground which is far below the accuracy potential of the DMC. Although resampling does not effect the geometry of the resulting virtual image in any significant way, it should be mentioned that in principle additional influences could be introduced during the resampling of the grey values of the virtual image. In general, it can thus be stated that the influence related to the virtual image generation is negligible and
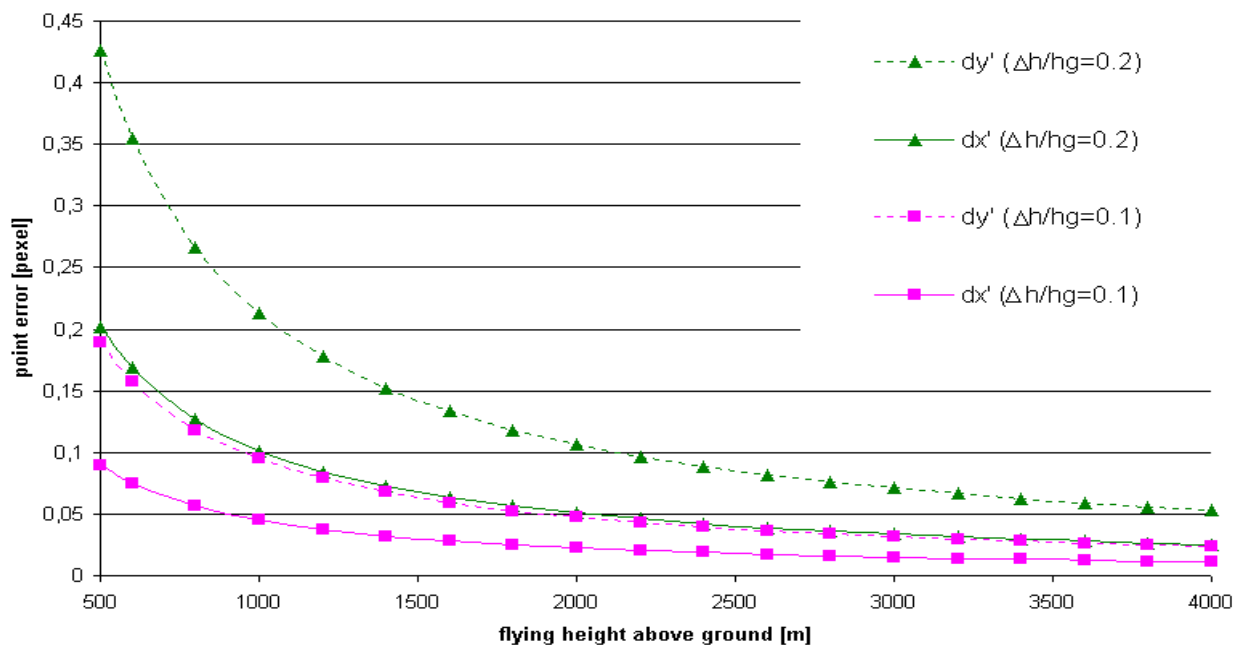
Fig. 5. Influences in dx' and dy' as a function of h_g and $\Delta h/h_g$

can completely be made to vanish by utilising the sub-images instead of the virtual images in the photogrammetric processing chain.

4   CONCLUSIONS

With the DMC development, Z/I Imaging as an end-to-end system provider completes the all-digital mapping system components for the photogrammetric and remote sensing practice. From both the technical and the practical point of view significant features of the DMC can be summarised as follows:

- Open for any new technological trends with its modular design
- Stable image geometry and superior image radiometry using CCD areal array chips
- Simultaneous acquisition of panchromatic and multi-spectral images
- Quick availability of image data
- Independent of the availability of GPS/INS measurements
- Compatibility to the existing DPWS using the central perspective virtual images
- Exploitable geometric accuracy potential using the original sub-images

All these properties and, in particular, its geometric stability and compatibility to the existing DPWS make the DMC readily applicable and thus more attractive for many applications, e.g. 3D city modelling and updating, disaster monitoring and documentation, infrastructure mapping, precision farming. With the DMC and other new digital sensors (Petri 2000), the era of digital airborne imaging is now starting for the mapping practice.

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