Experiences with the Production of Digital Orthophotos

Joachim Höhle

Abstract
Digital orthophotos increase the potential of land and geographic information systems considerably. In the workstations of these systems one can also produce digital orthophotos in black and white and color. Each step of the production process is illustrated in detail, and experience regarding the choice of parameters in the calculation programs is stated.

Introduction
Orthophotos may constitute an important element in land information systems (LIS) and geographic information systems (GIS). They principally serve as a background for topographic and thematic maps. They may, however, also form the basis of digitizing by means of which thematic maps are produced or updated. Other non-graphic information can be obtained from an orthophoto. Because the processing in an LIS/GIS is done with the aid of computers, the orthophotos have to be in digital form.

Digital orthophotos (sometimes called orthoimages) can be produced and handled on a GIS workstation.

It is the purpose of this paper to describe the production of digital orthophotos in a workstation of the above type, and to study the parameters which influence the quality of the orthophoto as well as the economy of their production. The objective of the investigation is to help organizations which consider producing or already produce digital orthophotos.

The Workstation
Modern LIS/GIS workstations can simultaneously and interactively process both line maps (vector data) and images (greytone matrices). Therefore, they are sometimes called "hybrid" systems. The large data quantities for an aerial photograph (approximately 100 Mb) demand a rather powerful computer with

- a large memory;
- a high processing speed;
- a graphics processor with memory for a great number of picture elements, each with 256 greytones;
- an extensive mass storage device; and
- input and output devices of high capacity (for example, magnetic tapes).

The software is comprised of the standard software of a graphic workstation (for example, the UNIX operating system), software for network communication, and application software.

The application software packages used in this work are produced by Intergraph Corp. They contain programs for image processing (IMAGER) and for elevation models (MODELER).

Moreover, there are programs for the production of orthophotos (IMCOR, ORBAT, and RECT _ PHOTO). These programs also use result files from the MODELER and IMAGER programs (Intergraph 1989/1992). The workstation used in this investigation, an Inter Pro 6280, has a 48-Mb memory and a 670-Mb harddisk, and data can be processed at a speed of 14 MIPS (million instructions per second).

The workstation and its software may be classified as a high-end workstation which is commercially available.

Steps in the Production of Orthophotos
The production of digital orthophotos in a workstation can be described through the following steps:

- Digitizing of the aerial photograph,
- Transfer of the digital image,
- Orientation,
- Preparation of the digital elevation model,
- Geometric transformation, and
- Mosaicking.

Each step will be explained in more detail below, and some experiences will be presented. It should be noted that commercial production might also include quality control, output formatting, and storage and retrieval.

Digitizing of the Aerial Photograph
Large-scale aerial photography has reached a high standard and, because of its high economy and simplicity, will not soon be replaced by digital imaging techniques. For the production of digital orthophotos, the analog photographs must first be transformed into digital form. This is done by means of special scanners; during recent years the instrument industry has developed several scanners for the standard 23- by 23-cm format film imagery (e.g., Zeiss, PS1/Intergraph, VX/VEXCEL, RM-1/Wehrli & Ass., and DiSC/ISM). Quality scanners allow for a pixel size of less than 25 μm and scan rates of 200,000 to 400,000 pixels per second. Using such a scanner, it is possible to scan aerial photographs even at the highest resolution (7.5 μm) in less than 20 minutes (Faust, 1990).

The quality of digital photographs is determined by their geometric and radiometric resolution, contrast, etc. Geometric and radiometric resolution not only determines the size of the main memory as well as of mass storage devices, but also the processing speed of subsequent processes. The selection of the pixel size for scanning is, therefore, a compromise between quality (including accuracy) and economy. In our tests, a pixel size of 25 μm by 25 μm was used.

For the radiometric resolution, 256 (2^8) grey levels, stored in one byte (8 bits), were chosen.

For further improvement of image quality, a histogram of the grey values was produced. Using this histogram, the ex-

Aalborg University, Fibigerstraede 11, 9220 Aalborg Oest, Denmark.

Photogrammetric Engineering & Remote Sensing, Vol. 62, No. 10, October 1996, pp. 1189–1194.

0099-1112/96/6210–1189$3.00/0

treme grey-value fields can be suppressed, the remaining fields can be stretched linearly, and/or an adjustment of contrast can be performed.

Transfer of the Digital Image

The scanned photograph is stored on a magnetic tape or on a CD-ROM. After conversion to the input medium of the workstation (e.g., cassette tape), it can be loaded into the workstation for further processing. A direct transfer via a network is also a possibility. Intergraph's COT format was used. The number of rows and columns of the image matrix and the scanning orientation are indicated in the header.

Orientation

The scanned and radiometrically corrected aerial photograph can now be transformed into a digital image with known interior orientation. Furthermore, its exterior orientation has to be determined, if this has not already been done during aerotriangulation. This reconstruction of the interior and exterior orientation of the aerial photograph is supported by the IMCOR and ORBAT programs, respectively. In the following, we comment on the underlying principles and on some peculiarities.

The *interior orientation* of the aerial photograph is indicated by the camera constant, the position of the fiducial marks, the principal point, and the radial distortion. Using a suitable transformation, the scanned image is resampled to a new matrix which will now be based on the coordinate system defined by the fiducial marks.

The measurement of fiducial marks takes place in the IMAGER software package. The entire image is displayed at a reduced resolution. However, the measurement of the fiducial marks takes place with a section of the image at full resolution. Using the "mouse," a measuring mark is pointed at the fiducial mark, and the coordinates (row/column) are stored in units of the pixel size (here 25 μm).

The *exterior orientation* can be determined with the aid of control points through spatial resection. The program ORBAT uses the results of the interior orientation and computes the results, i.e., the spatial coordinates of the projection center and the three rotations about the axes of the national coordinate system by means of a least-squares adjustment. The measurement of the image points also takes place in the IMAGER program. For further details on the algorithm used in the program, see Slama (1980).

Preparation of the Digital Elevation Model

For the area to be covered by orthophotos, a digital elevation model (DEM) must be prepared. This means that the elevations, which are arranged in a regular grid, have to represent the terrain. From these points, an elevation value for each pixel of the orthophoto will be derived. Errors in elevation can create planimetric errors in the orthophoto. At the corners of the model the planimetric error reaches its maximum and has about the same magnitude as the error in elevation. The accuracy of the elevation model has, therefore, a great influence on the accuracy of the orthophoto.

The use of a national elevation model is one approach. In Denmark, for example, the national elevation model was derived from the 5-m contour lines of the 1:50,000-scale topographic map. The distance between the elevation points is 50 m, and the accuracy of the elevation points is about σ_h = 1.6 m (Eggers *et al.*, 1989).

The other approach is to employ a special elevation model for orthophoto production. In Denmark it was derived from 1:25,000-scale photography. The distance between the elevation points is also 50 m, and they have an accuracy of σ_h = 0.8 m.

The accuracy of the required DEM can be improved by employing the same photography as that used for the orthophoto production (here, 1:18,000 scale). Such data material was used in this test. The profiles scanned in an analytical plotter were 32 m or 40 m apart. Within the profile, points were recorded automatically, but the operator selected additional breakpoints. In addition, breaklines and spot heights were recorded. All of these data were used to produce the elevation model. The modeling was done by means of triangles, which were then changed to a grid structure for output. The MODELER program also allows for validation of the model and for removing blunders. Table 1 provides an overview of the different DEMs. The improvements in accuracy when using breaklines for terrain modeling were considerable. When displaying the differences between the two DEMs with the grid size of 50 m (Orthophoto 1 and 2), errors of up to 3 m can occur. Therefore, the use of breaklines is recommended because the best overall accuracy can be obtained.

Geometric Transformation

The digital image can now be transformed into an orthophoto. It is necessary to find the grey value for each pixel in the orthophoto. *XYZ* coordinates exist for all the DEM points. Their positions in the digital image are found according to the photogrammetric projection equations by using the down to top approach. The parameters of the interior and exterior orientations form part of it. The relevant grey value is thus found through a suitable interpolation with the adjacent pixels (so-called resampling) and related to the orthophoto pixel. In order to reduce the processing time, this strict computation is not used for each pixel. Instead, a linear transformation is used for most of the pixels. Anchor points which are arranged quadratically in the orthophoto serve as control points. Their spacing is somewhat smaller than the DEM's grid size. Figures 1 and 2 illustrate and explain the concept in detail. All input data and input parameters for the computation program (RECT_PHOTO) are shown in Figure 3. For *resampling*, the nearest-neighbor method, bilinear interpolation, or cubic convolution can be used (see Figure 2). With cubic convolution, it is possible to choose other parameters in order to determine the shape of the sampling function. Also, the pixel size and the interval for the anchor points in the orthophoto, for which an exact computation according to the photogrammetric projection equations takes place, can be chosen. All of these parameters influence image quality and the processing time. Some experience is required in order to find an optimum solution for the efficient production of high-quality orthophotos.

Mosaicking

The orthophoto is normally produced from a single photograph. However, individual orthophotos sometimes have to

TABLE 1. CHARACTERISTICS OF VARIOUS DANISH DEMs

Name	Source	Type	Accuracy σ_h [m]
National	topographic map 5-m contours	GRID 50 m × 50 m	1.6**
Orthophoto 1 (State/KMS)	photography 1:25,000 scanning of profiles	GRID 50 m × 50 m	0.8*
Orthophoto 2 (Scankort/Höhle)	photography 1:18,000 scanning of profiles measurem. of breaklines	TIN+GRID 32 m × 24 m 50 m × 50 m	0.6**
Orthophoto 3 (Lysdal)	photography 1:20,000 scanning of profiles measurem. of breaklines	TIN+GRID 40 m × 40 m 20 m × 20 m	1.0**

TIN, means Triangulated Irregular Network.
*Specified value.
**Determined in tests.

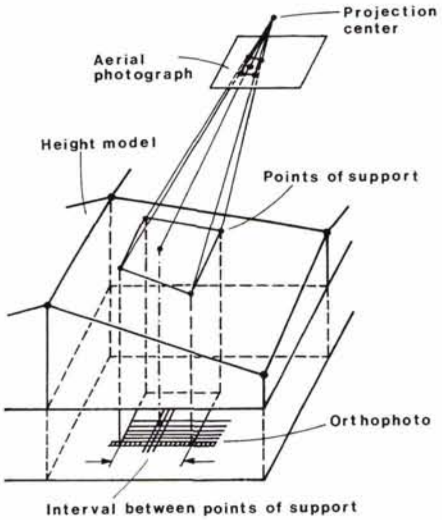

Figure 1. Computation of the photo point position for pixels in the orthophoto. The image coordinates for the grid points of the height model (DEM) and the points of support (anchor points) are calculated strictly, i.e., according to the photogrammetric projection equations. The remaining points/pixels are obtained by means of an affine transformation. The anchor points which are arranged quadratically in the orthophoto serve as control points. In this way it is possible to save considerable processing time. The image quality, however, can deteriotate somewhat, because a zigzag effect on straight lines such as building edges is produced by that procedure.

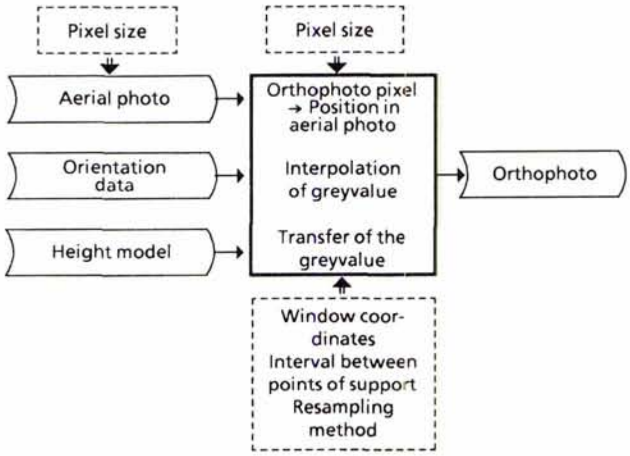

Figure 3. Input data and input parameters for computation of a digital orthophoto.

be assembled into a photo block. Then a radiometric matching of the boundary and overlap areas has to be carried out. Various methods are proposed to achieve a homogeneous mosaic (for examples, see Murai (1980) and Hood (1989). In a Ph.D. thesis at the Danish Technical University in Copenhagen, a distortion surface model was used. The parameters of the polynomial surface were determined by a least-squares adjustment using grey values in the overlap areas of the original images as observations (Klinting, 1989).

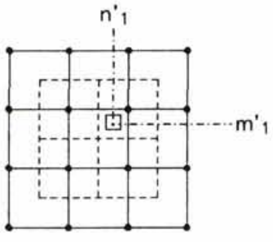

Figure 2. Derivation of a grey value $d(n'_1,m'_1)$ by means of adjacent pixels. ⊡, Image point of an orthophoto pixel. •, Pixel center.
In the nearest-neighbor method, one takes the grey value of the adjacent pixel. In linear interpolation, one calculates the grey value as the weighted mean of the four directly adjacent grey values. In cubic convolution, one calculates the grey value as the weighted mean of the adjacent 4 by 4 grey values.

Test and Results

Three different orthophotos were produced with the programs described. Figure 4 shows one of the examples. Moreover, various tests were carried out regarding the effect of the individual parameters on processing time and image quality. Details about the examples are listed in Table 2.

The experiences made at each step of the processing of the orthophoto are summarized below for all three examples.

Digitizing of the Aerial Photographs

The black and white aerial photographs were digitized with the Optronics 5040 large-format scanner or the Zeiss/Intergraph Photo Scan PS1. The pixels had a size of 25 µm by 25 µm or 30 µm by 30 µm with 256 grey values. The image matrix thus consisted of about 9800 by 9800 pixels, which required a storage capacity of about 92 Mb. In the case of the color photograph, the required capacity was 168 Mb, or 56 Mb per primary color (red, green, blue).

The digitizing took about 20 minutes per black-and-white photograph or 1 hour per color photograph. The digital images were stored on magnetic tapes and delivered by mail from the Scan-Service.

Transfer of the Digital Image

The digital image was loaded into the workstation from a cassette tape. A conversion from one data unit to another was therefore necessary.

The input from the cassette tape into the workstation takes about 15 minutes for each 92-Mb image.

Orientation

The orientation of the image has two parts: The interior and the exterior orientation. In the first part the fiducial marks have to be measured, and an affine transformation is carried out in order to establish an image coordinate system. The exterior orientation requires the measurement of control points. The parameters of the exterior orientation are possibly known from the orientation on the analytical plotter, when the DEM measurements are carried out. The measurement of control points in Example 1 was influenced by insufficient image quality (in the original photograph), and by the full-pixel accuracy in pointing. As in the case of the fiducial

Figure 4. Digitally produced orthophoto of a 2- by 3-km area in Denmark. Geometric resolution: 0.4 m by 0.4 m on the ground.

marks, it took place in a very enlarged section of the digital image which was displayed at full resolution. The exterior orientation was calculated with only one photograph. The residual errors can be seen in Table 3.

Geometric Transformation

For the production of orthophotos, it is necessary to optimize processing time, accuracy, and image quality. The influence of the different input parameters on the *computation time* is demonstrated in Figures 5, 6, and 7. It turns out that processing times of about 10 minutes can be achieved, if the interval of the anchor points remains above 16 m, the pixel size on the ground is not smaller than 0.5 m, and the grey value is derived by means of the nearest-neighbor method.

If cubic convolution is used, the parameter which determines the shape of the sampling function has no influence on the computation time. On the other hand, the memory size greatly influences the processing time. For these tests, 40 Mb of the main memory was available for the program, and no other programs were running concurrently. If only 2 Mb were available, the processing time would nearly be doubled.

The geometric accuracy of the orthophotos mainly depends on the accuracy of the elevation model and of the orientation parameters of the aerial photograph. The color orthophoto of Example 3 had a point error (RMSE) of $\sigma_p = 0.9$ m on the ground or $\sigma_p' = 45$ μm (1.5 pixel) in the image. Two-hundred eighty-two check points were used in the test. The interval of anchor points was 15 m. Nearly the same results were obtained with smaller intervals, but the processing time increased to 91.5 hours at a 1-pixel interval (Lysdal, 1993).

The *image quality* is especially affected by the pixel size and by the resampling method chosen. With the nearest-

Table 2. Details of the Input Data for Orthophoto Production

	Example 1	Example 2	Example 3
Aerial photograph			
Emulsion	b&w	b&w	color
Photo scale	1:13,500	1:18,000	1:20,000
Pixel size	25 μm	25 μm	30 μm
Elevation model			
Interval of the elevation points	40 m	50 m	20 m

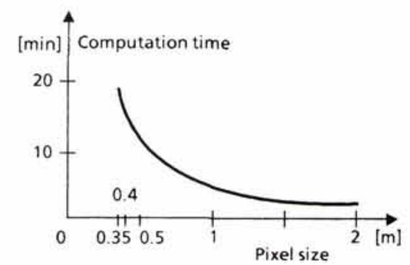

Figure 5. Computation time as function of the pixel size.

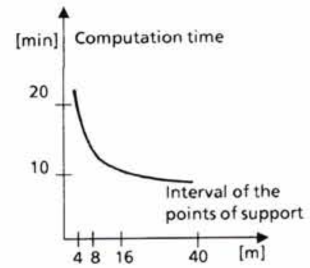

Figure 6. Computation time as function of the intervals of the anchor points (pixel size px = 0.5 m).

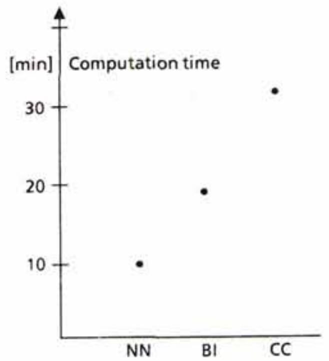

Figure 7. Processing time as function of the resampling method. NN, nearest neighbor; BI, bilinear interpolation; CC, cubic convolution (pixel size, 0.5 m; interval of the anchor points, 16 m).

neighbor method, errors of up to half a pixel may occur, which can show up in the grey value structure. The cubic convolution causes relatively long processing times. If the pixel size in the aerial photograph is small (for example, 25 µm), the image quality will hardly be influenced by the resampling method. In this case, the nearest-neighbor method was chosen because this shortens the processing times (by a factor of 3). In Figure 8, an enlarged section of the digitally produced orthophoto is shown. The individual pixels, which are 0.4 m by 0.4 m in the terrain, can hardly be seen.

Some Economic Aspects

The processing times for the production of a black-and-white digital orthophoto; when using the Intergraph workstation, are shown in Table 4.

A digital orthophoto in black and white can thus be produced in about 2 hours. Additional time may be necessary for preparation, quality control, mosaicking, output formatting, and storage and retrieval. Data collection for the elevation model and its editing may also require additional time.

In the case of color orthophotos, the times for digitizing the aerial photograph, the transfer of the digital image, and the geometric transformation are about three times greater. The times for the geometric transformation will increase by a factor of 9 when sampling by cubic convolution is applied in order to improve the image quality.

Conclusion

The user of a high-end workstation is able to produce digital orthophotos in black and white and color. Processing times of about 10 minutes can be achieved for black-and-white orthophotos, while the time increases by a factor of 3 when color material is transformed. These times cover the geometric transformation only. Various preparation times may be necessary in addition.

A planimetric accuracy of σ_p = 0.045 µm (RMSE) at photo scale, or σ_p = 0.9 m on the ground, was obtained in tests with a color orthophoto.

The derived orthophotos can be used within geographic information systems, where they serve as a background for topographic or thematic maps in vector form or as source for new information.

TABLE 3. RESIDUAL ERRORS AT THE CONTROL POINTS IN THE COMPUTATION OF EXTERIOR ORIENTATION.

Example	n	$\sigma_{x'y'}$ [µm]	$\sigma_{x'y'}$ [pixel]	σ_p [m]
1	10	55	2.2	1.0
2	10	29	1.2	0.7
3	20	16	0.5	0.5

n, number of control points.
$\sigma_{x'y'}$, RMSE at the image.
σ_p, RMSE on the ground (vector).

Figure 8. Section of the produced digital orthophoto in combination with a 200- by 200-m square (geometric pixel resolution, 0.4 m by 0.4 m on the ground; resampling method, nearest neighbor).

Table 4. Processing Times for Black-and-White Digital Orthophotos Produced by the Intergraph Workstation

	Minutes
Digitizing of the aerial photograph*	20
Transfer of the digital image**	15
Orientation	
(input of the control points, measurements, calculations)	70
Preparation of the elevation model	
(Choice of section, resampling)	5
Geometric transformation	10

*Carried out in a separate process (off-line).
**Without reformatting to another data carrier.

References

Eggers, O., S. Ellegaard, L. Hoelledig, and P. Norvin, 1989. *From Contourlines to a Digital Height Model*, final thesis at Aalborg University, 113 p.

Faust, H.W., 1990. Digitalisierung photogrammetrischer Bilder, *Zeitschrift für Photogrammetrie und Fernerkundung* 1, 6 p.

Hood, J., L. Ladner, and R. Champion, 1989. Image Processing Techniques for Digital Orthophoto Production, *Photogrammetric Engineering & Remote Sensing*, 55(9):1323–1329.

Intergraph Corp., 1989/1992. *Documentation of the program packages Rectify and ISIR.*

Klinting, A., 1989. *Mosaicking Digital Orthophotos*, Institute for Surveying and Photogrammetry at the Danish Technical University, Copenhagen, 109 p.

Lysdal, E., 1993. *Production of a Digital Color Orthophoto by Means of a Height Model Derived from a Digital Map*, diploma thesis (in Danish), Laboratory for Photogrammetry and Surveying, 92 p.

Murai, S., T. Okuda, and M. Akijama, 1980. Digital Mosaic of Colour Aerial Photographs, *Proc. ISPRS Congress, Comm. IV*, Hamburg, 23(34):570–578.

Slama, C. (editor), 1980. *Manual of Photogrammetry, 4th Edition*, American Society of Photogrammetry, Chapter 2, pp. 88–101.

(Received 22 July 1993; accepted 17 July 1995, revised 29 August 1995)