ON PERFORMANCE OF DIGITAL OFF-LINE SYSTEMS FOR AUTOMATIC PRODUCTION OF DTM DATA

B. Makarovič
Photogrammetry Department, ITC, The Netherlands
Commission II, Working Group II-2

ABSTRACT

The main process stages are defined together with factors influencing performance, and sources of disturbances. The corresponding concepts and tools for theoretical assessment of performance and the quality indicators are also reviewed. The most crucial problem is assessment of parallax accuracy, which has not yet been solved satisfactorily. The corresponding estimators can be verified by means of specific inputs with known matching characteristics.
Fidelity of automatically produced DTM can be represented by a composed Transfer Funtion, and from it the critical frequency (terrain resolution) can be defined.

I. INTRODUCTION

The aim of the paper is to outline a framework for organisized assessment of the performance of systems for production of DTM data by digital off-line (time-delayed) technique. Such a framework and corresponding considerations make the problem area more transparent and thus, in turn, contribute to improved systems.

The main process stages and the corresponding input-output data are defined in figure 1.

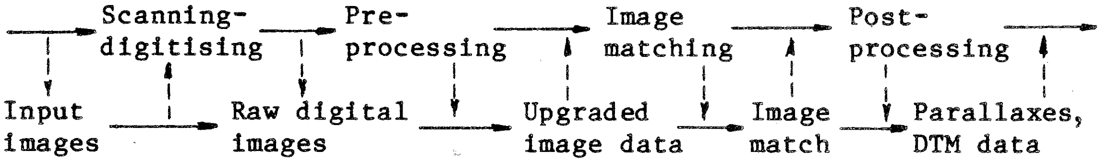

Fig. 1 Process stages and data.

Performance can be assessed by the following approaches:
1. Experimantal tests using real data inputs or artificial data;
2. Analytical, by means of theoretical tools;
3. Semi-analytical, i.e., by a combination of experimental tests and theoretical analysis.

This paper is concerned with theoretical analysis. The experimental approach was implemented by the ISPRS Working Group II/2, subgroup for Correlation Test.

The contents of this paper are structured in two sections. The first, gives an overview of the influencing factors and sources of disturbances in the successive process stages. The second outlines the quality indicators for pictorial and geometric data, and it contains some concepts and tools for theoretical quality assessment. The contents are arranged according to the sequence of data flow indicated in figure 1. Emphasis is placed on the most crucial and complex problems.

II. INFLUENCING FACTORS AND SOURCES OF DISTURBANCES

Influencing factors may have negative and/or positive effect on performance and reliability. Disturbances originate in approximate algorithms, physical processes, incrementation of data (spatial, intensity), filtering (and interpolation), thresholding, and eventually in rounding-off numerical data. The last, however, can be made insignificant and will therefore not be considered further.

II.1 Scanning-digitizing

The factors and sources involved can be differentiated into the geometric and pictorial (intensity). Geometric factors are the spatial step (increment) between adjacent pixels, pixel size, and use (or not) of the geometry of the photogrammetric model (e.g., epipolar geometry). Geometric disturbances originate in relative orientation (if model gemoetry is used), in sensor positioning, and in the spatial lay-out (i.e., step size and phase) of pixels.
Pictorial factors concern illumination intensity, sensor acuity, size of sensing area, integration time at sampling, and intensity increment size. Disturbances originate in uneven illumination, varying responsivity of sensors, noise, and in incrementation of intensity.

II.2 Pre-processing

If properly applied pre-processing upgrades raw image data. Nevertheless, the operations involved [4] cause some losses in both geometric and pictorial domains. These losses can be suppressed and some gains achieved by merging different input data sets, excluding anomalous regions, correcting data, analysing data and extracting distinct features, and by synthesising new image data. Significant losses, however, can be attributed to resampling, image transormations (intensity), and filtering and thresholding (for compression). Data segmentation and structuring can improve the quality of image matching at the expense of reduced time-efficiency. This also holds for integration of external information (to be used at image matching and/or post-processing). Inadequate data segmentation and structuring, and improper use of external information may cause substantial losses in both terms of quality and time-efficiency.

II.3 Image matching

The most essential factors concern the strategy, algorithms and techniques of matching [4]. These are strongly interdependent and have both positive and negative effects on performance. More sophisticated procedures tend to increase accuracy and reliability of matching, but are less time-efficient, and vice versa. In off-line systems, however, time-efficiency is less important.
Disturbances can be attributed to image data (i.e., distortions) and

to the matching process. Image data are distorted geometrically and radiometrically (intensity). Geometric distortions originate in internal imaging, external (camera) attitude, and in terrain relief (and obstacles on it). Radiometric disturbances emerge from the varying reflectance of the same objects at imaging, shadows, lack of detail, periodic patterns, etc.
When matching, disturbances occur if the strategy, algorithms (and /or their parameters) or the techniques are deficient.

II.4 Post-processing

Post-processing implies parallax editing and DTM calculations [4]; thus the influencing factors refer to these two sub-stages. Parallax editing involves the following operations: inclusion of external imformation, collective processing, and a-posteriori exclusion of poorly matched regions (if not rejected before). They contribute to improved quality of the results.
Several influencing factors are involved in supplementary DTM calculations. The corresponding operations are interpolation, resampling (DTM), and compression. The corresponding loss in accuracy is usually balanced by gain in data utility.
Disturbances occur in both post-processing sub-stages. Prior to parallax editing representative points of the matched pairs of segments must be defined. The transfer of such a point from one segment into its conjugate implies a potential disturbance. Other disturbances occur in absolute orientation, approximate algorithms for the DTM calculations, filtering (for smoothing), compression, resampling, etc.

III. INDICATORS AND CONCEPTS FOR QUALITY ASSESSMENT

Quality control should be applied in all stages of the process. To this end, appropriate concepts and theoretical tools need be selected and/or devised. These apply to the data inputs and outputs of the sequential process stages (figure 1).
Distortions in data are caused by disturbances in the process. A differentiation can be made between the pictorial and geometric quality components of the data in the successive process stages (table below). At image matching, the pictorial and geometric components are merged.

Sequential data Component	Input image	Digital raw data	Upgraded data	Image match	Parallax data	DTM data
Pictorial	x	x	x	x		
Geometric	x	x	x		x	x

Table: Components of quality for the sequential data sets.

Parallaxes and DTM data, however, contain merely geometric data. Hence, the performance considerations should be structured accordingly. In the following, an overview is given of the indicators, concepts and tools for assessment of the performance.

III.1 Input images

The concepts and quality indicators can be differentiated into deterministic and statistical and further into those referring to image quality (i.e., pictorial) and to spatial location (i.e., geometric).
Image quality: deterministic concepts (and tools) are Fourier Transform (or power spectrum), dynamic range, resolution (spatial, intensity, spectral), and modulation transfer-function (MTF-imaging).
Common statistical concepts are signal-autocovariance (and variance), intensity hystogram, spread function, noise-autocovariance (and variance), signal-to-noise ratio (SNR), and noise-power spectrum.
Geometry: Deterministic concepts include the different models of regular distortions, such as for film, camera, and atmosphere.
Statistical concepts (and indicators) comprise weight functions, covariance (or correlation) functions, variances, and various statistics (error distributions), all referring to geometric location.

III.2 Digital raw image data

The concepts and quality indicators can be classified as those for input images.
Image quality: Deterministic indicators are intensity increment (or resolution), spatial increment (and pixel size), Fourier Transform (FFT and/or power spectrum of digital image), and Transfer Function (of rastered image) and corresponding limiting frequency [2], [6].
Statistical measures are autocovariance (and variance) of digital image, level of noise, SNR, and different statistics (distributions)

Geometry: Deterministic indicators are model deformations caused by relative orientation, and errors in positioning sensors at sampling..
Statistical quality measures are standard deviations caused by spatial incrementation (i.e., image raster : $\sigma = \Delta:3.46$, where Δ is increment size; [2]) and locational-error statistics.

III.3 Upgraded image data

The concepts and quality indicators should reflect the specific choice of the pre-processing operations, which can vary from one case to another.
Image quality:
The degrading effect of data resampling can be assessed by a composed Transfer Function (annex 1), whereas that of linear filtering can be handled by a single Transfer Function [2]. Thresholding imposes limits on either intensity or frequency for selective data exclusion (annex 2). Corresponding losses are quantifiable, e.g., in terms of standard errors. Image transformations (intensity) are accompanied with losses too; the corresponding assessment, however, is beyond the scope of this paper. Synthesising image data does not introduce significant losses if done with sufficient care.
Failures and errors in image analysis and feature extraction are hardly tangible.

Geometry:
Resampling has a twofold effect: It degrades spatial resolution and reduces locational (measurement) accuracy ($\sigma_r = \Delta:3.46$). Gridding of the external information into image-raster does not necessarily cause significant loss (but it is quantifiable). Geometric corrections for deterministic errors can be accurate enough. Locational errors after pre-processing can be analyzed by means of statistical tools.

III.4 Image match

At matching, pictorial and geometric data are merged, which makes theoretical assessment of matching accuracy very complex. The corresponding quality indicators depend on the matching technique [4]. In the case of a sequential search the common indicators are the maximum of similarity assessment function (i.e., peak of correlation function) and its maximum slope (at the point of inflection).
Matching accuracy depends also on the step size between successive trials, and, further, whether or not a curve is fitted to discrete points (i.e., results of trials) and the maximum is determined by calculation.
If the least squares fit is applied, then the quality of match is indicated by the descrepancies in intensity [1] or in location [3], and the corresponding standard errors.
Overall accuracy of matching can be assessed from the statistics of single matches involved, e.g. hystrograms and standard errors.
If resampling is applied iteratively during matching, image data are degraded gradually, which can affect adversely the matching accuracy.
Reliability depends strongly on the input images, matching strategy, acceptance threshold and the a-priori exclusion of anomalous regions. Reliability is quantifiable in statistical terms (e.g., as percentage of successful matches).
Time efficiency is not essential in off-line systems, though it is not negligible. It can be expressed by cycle-times per trial, per match, per full patch, and/or per full model.

III.5 Parallax data

Parallaxes are the gemometric by-product of image matching [4]. The corresponding quality indicators are parallax accuracy of individual points, parallax fidelity of a neighbourhood (i.e. a parallax "profile" or a "surface"), reliability, and time-efficiency.
Parallax accuracy is the most important criterion for performance assessment. It depends on the accuracy of matching segments and on definition of representative conugate points in the segments (annex 3), geometric distortions (caused by model deformation), and on thresholding at data compression [5].
Indicators for parallax accuracy are standard parallax error (annex 6) and error distributions (spatial, statistical).
Accuracy can be upgraded by collective processing of local parallax data. The fidelity of such data (e.g., a parallax profile or surface) depends on the interval between the adjacent (representative) points, overlap of the adjacent image (target) segments, and the smoothing filter (if applied).

Each of these partial effects can be assessed by the corresponding Transfer Function (annex 5) [6].
Reliability of parallax data is determined by image matching (vide III.4). It can be improved by excluding (still remaining) anomalous regions, and by collective parallax editing.
Time efficiency is determined by the mean editing time, inclusive quality control, e.g., per single parallax, per epipolar parallax profile, or per model.

III.6 DTM data

The accuracy indicators are similar to those for parallaxes. Additional errors, caused by absolute orientation, DTM data compression, resampling and smoothing, can be quantified as indicated in annexes 1 and 2, by a Transfer Function for smoothing [2], and by applying the law of error propagation (to orientation).
Fidelity of a profile (or surface) restored from DTM is determined primarily by the fidelity of the corresponding parallax data. Resampling (to a uniform grid DTM) and linear filtering cause further degradation. The resulting fidelity can be represented by the composed Transfer function (annex 6); its limiting frequency determines the terrain resolution.
Reliability corresponds to that of the parallax data. By integrating external (a-priori) information in the DTM, reliability and accuracy can be improved.
Time efficiency is dominated by determination of parallaxes. Cycle-times, for DTM calculations, editing and quality control are, however, not negligible, though operation is time relaxed.

IV. CONCLUSION

An analytical approach for performance evaluation of systems for automatic DTM production is very complex. In this paper I have attempted to draw up a framework for the assessment of inputs and outputs of the sequential process stages. The corresponding concepts and analytical tools are still incomplete. The most crucial is theoretical estimation of parallax accuracy for which adequate tools are not yet availabe. The problem can be handled semi-analytically, i.e., by assessing parallax accuracy experimentally, whereas for other operations analytical tools can be used.
The purpose here has been to make the problem area, as a whole, more transparent, without focussing on individual process stages or operations. Emphasis has been placed, however, on those operations, which have previously received little or no attention, i.e., resampling, thresholding, parallax accuracy and fidelity of DTM data. Improved insight and thus understanding of the performance problems can contribute to amendments of existing systems, development of new systems, and to better quality control.

REFERENCES:

[1] Ackermann, F. Hochgenaue digitale Bildkorrelation, 39th Photogrammetric Week, Stuttgart, 1983

[2] Makarovič, B Tempfli, K. Digitising images for automatic processing in photogrammetry, ITC Journal, 1979-1, Enschede.

[3] Turgood, J.D. Mikhail, E.M. Photogrammetric analysis of digital images, ISPRS Commission III Symposium, Stockholm, 1982

[4] Makarovič, B. Automatic production of DTM data by digital off-line technique, ISPRS Congress, Commission II, Rio de Janeiro, 1984

[5] Makarovič, B. A test on compression of DTM data, ITC Journal, 1983-2, Enschede

[6] Tempfli, K. Makarovič, B. Transfer Functions of interpolation methods, Geo-processing, 1, Amsterdam, 1979

ANNEX 1 Resampling

The original digital image is assumed to be represented by a raster of pixels with interval d (where d equals pixel size). The corresponding Transfer Function [2] is $TF_{old} = f(d, r_p)$, where r_p is a rectangular function representig a pixel (fig. 2).
Original data can be resampled, i.e., to form another raster of pixels having a different orientation and density. The Transfer Function of the new raster is $TF_{new} = f(\bar{d}, \bar{r}_p)$, where $\bar{d}$ is the new interval and $\bar{r}_p$ is the new (rectangular) function. The intensity values of new pixels, however, are determined by interpolation (usually linear) from the nearest neighbouring old pixels. Hence, the Transfer Function for interpolated vaues in the original (old) raster is

$$TF_{old/int} = f(d, \text{interpolation})$$

The combined effect of interpolation and of the new raster (interval $\bar{d}$) can be represented by

$$TF_{resamp} = TF_{old/int} \cdot TF_{new}$$

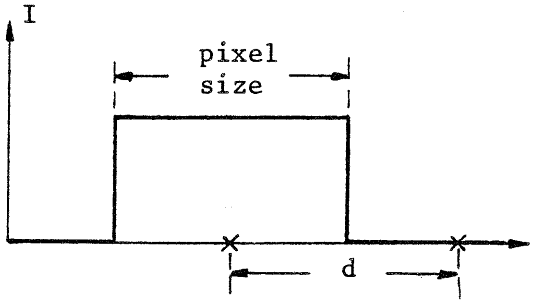

Figure 2: Rectangular function representing a pixel.

ANNEX 2 Thresholding

Thresholding serves for selective exclusion of data in the intensity (or amplitude) or the frequency domain. Thresholds can be specified for the lower and/or the upper bound.
The effect of amplitude thresholding is shown in figure 3. All amplitudes smaller than the lower bound and/or greater than the upper bound (e.g. gross errors) are rejected. The data can be segmented according to several (e.g., adjacent) specified pairs of the lower and upper bounds for amplitude.

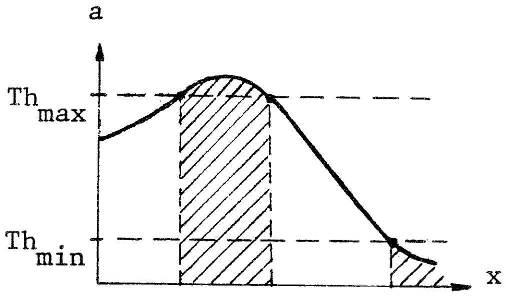

Fig. 3: Amplitude thresholding

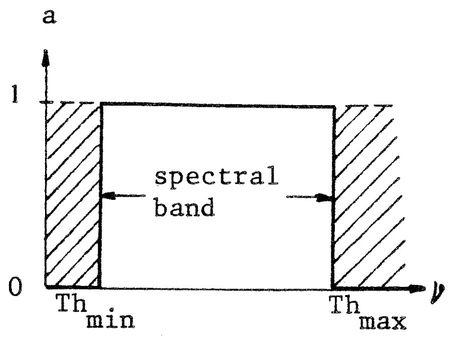

Fig. 4: Frequency thresholding

The effect of frequency thresholding can be represented by a rectangular Transfer Function (figure 4). By specifying several (e.g., adjacent) pairs of lower and upper bounds for frequency, the data can be segmented into frequency bands.

ANNEX 3 Parallax accuracy

Suitable tools are needed for theoretical assessment of the parallax accuracy. The latter comprises two error components, i.e., the matching error of conjugate segments, and the tranfer error of a representatitve point from one segment (i.e., target) to its conjugate (search segment).
Matching error is the most difficult to model, because it comprises a number of the pictorial and geometric factors. These are: intensity variation, deterministic distortions (in intensity and geometry), random distortions, (i.e., noise in geometry and intensity), pixel size and image increments (in intensity and space), segment size (1D or 2D sample), suitability of pre-processing (intensity, geometric), and image matching (strategy, algorithms, and techniques).
Modelling the effects of all these influencing factors on matching accuracy is a very complex problem, which has not yet been solved satisfactorily.
Error at transfer of a representative point selected in one segment to its conjugate cannot be modelled in deterministic terms. The point selection criteria can be: the midpoint of a segment, a weighted mean, or a distinct point. Point transfer to conugate segment is by a (linear or non-linear) transformation. The corresponding transformation "surface" (or curve) does not fit accurately the terrain relief within the segment which introduces a small parallax error.

Most of the listed influencing factors can be differentiated further. Errors of matching and point transfer are mutually independent. Points need be selected and transferred only for the successfully matched pairs of segments.

ANNEX 4 Matching quality estimators

Suitability of the existing theoretical accuracy estimators can be examined experimentally, by logical analysis, and/or by means of artificial data inputs for which the quality of matching is known.
In experimental tests, the attained accuracy is compared agains the corresponding theoretical expectation.
Logical analysis can be applied to the assessment algorithms, inclusive the influencing factors involved (annex 3). Let us consider two typical examples: modelling the effect of noise (in intensity), and "the number of observations" at matching by the least squares method.
If gradient (image-) data are used for matching, noise should be removed prior to differentiation; otherwise gradient data are strongly distorted. This, however, reduces the reliability and accuracy of matching.
In the case of matching by the least squares method, the effective sample size (i.e., number of observations) is usually much smaller than the number of pixels involved (in a target segment). This is because many of the pixels do not contribute to a match in the case of lacking signal variation.
Instead of logical analysis of the algorithm we can regard it as "black box". Selected artificial data inputs can be used, for which the matching accuracy is predictable - at least roughly. Thus the approach is based on comparison of the theoretical estimates with the anticipated results. Typical examples of selected artificial inputs are: linearly changing intensity, including zero-change (which does not provide a match at all), a step input - resulting in ideal match, an input having SNR<1 - providing a low matching accuracy, and a periodic input - resulting in multiple matches.

ANNEX 5 Fidelity of parallax data

Fidelity of a parallax profile (or surface) is affected by several process parameters, i.e., the interval Δ between adjacent parallax points (figure 5), the overlap o of adjacent target segments, and the filter(s) - if applied to raw parallax data.
Because the input - output relationship is essentially linear, the fidelity of a parallax profile (or surface) can be represented by a Transfer Function.
The effect of incrementing (Δ) a parallax profile can be considered in combination with interpolation of the intermediate parallax points [6]. The corresponding fidelity is thus $TF_{\Delta} = f(\Delta, \text{interpolation})$, assuming that adjacent parallax-points are uncorrelated.
Correlation occurs, however, if the adjacent target segments overlap (figure 5).

By assuming that all pixels of a segment contribute equally to a match (which holds only statistically, but not for individual segments), a target segment can be regarded as a rectangular sampling function. From [2] it follows that fidelity decrases by increasing the overlap o: $TF_o = f(r_t, o)$, where r_t is the rectangular sampling function representing the target, and o is target overlap.

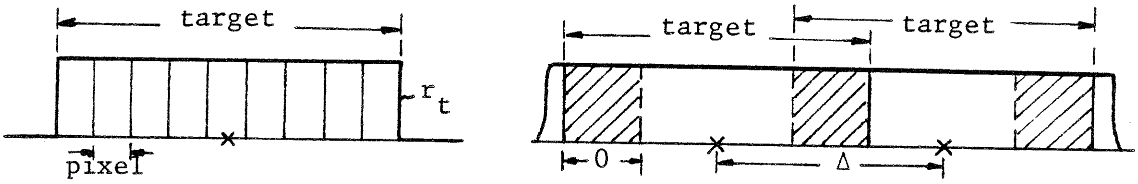

Fig. 5: Overlapping target segments.

If a linear filter is applied for smoothing parallaxes [6], the corresponding degradation effect can be represented by: $TF_f = f(\text{filter})$. The combined degrading effect of incrementing (Δ) of overlapping segments (o), and of filtering can be represented by the Transfer Function $TF_p = TF_\Delta \cdot TF_o \cdot TF_f$.

ANNEX 6 Fidelity of DTM

In an ideal case, the fidelity of the DTM would be identical to that of the corresponding parallax data, i.e., $TF_t \equiv TF_p$.

Raw DTM data have to be converted and resampled, e.g., from epipolar profiles to a uniform grid in a terrestrial coordinate system. The corresponding Transfer Function $TF_{\bar{\Delta}} = f(\bar{\Delta}, \bar{r})$, where $\bar{\Delta}$ is the new grid interval and $\bar{r}$ is a (virtually) rectangular function representing a new grid cell.
If parallax data were not smoothed before (annex 5), a linear smoothing filter can be applied to DTM data; hence, $TF_f = f(\text{filter})$. Fidelity of the resulting DTM is therefore determined by

$$TF_{DTM} = TF_p \cdot TF_{\bar{\Delta}} \cdot TF_f.$$

For a still acceptable (minimum) fidelity, the corresponding terrain resolution (i.e., the smallest resolvable terrain form) can be determined by means of the TF_{DTM} [6].