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Baltsavias, Emmanuel P.

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TEST AND CALIBRATION PROCEDURES FOR IMAGE SCANNERS

Emmanuel P. Baltsavias
Institute of Geodesy and Photogrammetry, Swiss Federal Institute of Technology
ETH-Hoenggerberg, CH-8093 Zurich, Switzerland
Tel.: +41-1-6333042, Fax: +41-1-6331101, E-mail: manos@p.igp.ethz.ch

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ABSTRACT

Film scanners will be used for many years to come and it is well known that not even the best and most expensive scanners are not free of errors. Scanner testing and calibration procedures are necessary to achieve a high geometric and radiometric scanner performance. It is also a means to produce or make use of cheaper scanners that do not rely on expensive mechanical positioning and optical parts. The paper refers to flatbed scanners employing linear or area CCDs, thus to both photogrammetric and DeskTop Publishing (DTP) scanners. It first presents different slowly and frequently varying errors of geometric and radiometric nature and their sources. The focus of the paper is on general testing procedures for high precision scanning. Different test patterns for detection of various errors and requirements on their quality are presented. Appropriate conditions for performing the tests are formulated. Test procedures for detecting and correcting various errors using test patterns are presented. Finally, some requirements for scanner vendors are proposed. The work is closely related and was partially done within the OEEPE/ISPRS Working Group on the Analysis of Photo-Scanners.

1. INTRODUCTION

The aim of this paper is to present general, possibly device independent, testing procedures for high precision, high resolution scanning. The tests refer mostly to flatbed scanners employing linear or area CCDs. Thus, they are applicable to photogrammetric scanners and flatbed DTP scanners. For drum scanners similar tests and test patterns on stable Estar thick base film could be used. First, a classification of errors in slowly and frequently varying, and a listing of the major geometric and radiometric problems is given. The tests are divided in off-line (periodic, modelling slowly varying errors) and on-line (for each scan, modelling frequently varying errors). Then, a set of important test patterns is described including resolution charts, grey scale and colour wedges, test charts for tonal and colour rendering, test patterns of fundamental features like lines and dots, and grid plates. Certain requirements for such test patterns, like stability, planarity, density of patterns, pattern size, scanner stage area coverage etc. are subsequently presented. A test pattern for on-line tests of scanners employing one or two scanning swaths is further proposed. Different commercial vendors of test patterns are given. The next step is the specification of the test conditions for an easy detection and quantification of geometric and radiometric errors. Finally, testing procedures are outlined. It is proposed to correct first the radiometric errors and then the geometric ones. For detection and evaluation of the test patterns, digital image analysis techniques employing automated, fast, and subpixel accurate algorithms should be used. Instead of using global modelling corrections for all geometric errors, e.g. by high degree polynomials, it is proposed to separate the errors in temporally stable and unstable and model them separately. Furthermore, the errors should be modelled separately in each direction (especially with linear CCDs), and whenever possible in an explicit manner, as for example for lens distortion. Requirements for calibration of scanners by the vendors are also proposed. This includes factory calibration, service and installation calibration, and on-line calibration before each scan. For the latter one, different testing procedures, affecting particularly the radiometry, are proposed. Such testing procedures are necessary even with expensive, photogrammetric scanners. An overview of scanners and references on scanner tests and calibration procedures is given in Baltsavias and Bill, 1994.

2. ERROR TYPES AND SCANNER PROBLEMS

Error types can be classified according to different criteria, e.g. geometric and radiometric errors, or slowly and frequently varying errors. In the following the second classification will be used. Some errors refer only to area CCDs, others to linear

CCDs or multiple optically butted linear CCDs. Reference to these specific sensors in the text will be made using the acronyms A-CCD, L-CCD, ML-CCD respectively. Photogrammetric scanners employ either area CCDs that scan the image in tiles or linear CCDs scanning in multiple swaths. Flatbed DTP scanners use one or multiple linear CCDs to scan the image in one swath. Here only the major errors will be mentioned. Other errors can occur depending on the design, construction, and parts of each individual scanner. Whether some errors are slowly or frequently varying depends on the quality and stability of the scanner, e.g. in photogrammetric scanners the positioning mechanism is accurate and stable, while in DTP scanners the positioning errors vary from scan to scan or even within one scan. For linear CCDs the following convention will be used. Horizontal direction is the direction of the linear CCD, vertical the direction of the scanning movement.

A. Slowly varying errors

1. Distortions due to lens or other optical parts

   This refers mainly to geometric errors like symmetric radial and tangential distortion. Radiometric errors like vignetting, shading, and secondary reflections can also be introduced by the optics.

2. CCD blemishes (A-CCD)

   They usually occur only with large area CCDs. Blemishes are single pixels, lines/columns or areas whose grey values differ significantly (e.g. 16 grey values or more) than the average grey level of their neighbourhood due to fabrication faults.

3. CCD misalignment and overlap (ML-CCD)

   The multiple CCDs may have different direction or not be collinear. If their overlap is not correctly estimated by a sensor calibration, then overlaps or gaps will occur.

4. Subsampling errors (L-CCD, ML-CCD)

   When scanning with a resolution less than the original one, the pixels in horizontal direction are low-pass filtered and resampled, while in vertical direction larger pixels are created by increasing the scanning speed. This leads to different treatment of horizontal and vertical features and can lead to loss of information if the scanning speed is not increased by the correct amount and is not properly synchronised to the integration time.

5. Smearing (L-CCD, ML-CCD)

   Due to the high scanning speed horizontal features, especially lines, will appear thicker and with lower contrast than vertical ones. This effect corresponds to a low-pass filtering.

6. Focusing

   The sensor plane should be parallel to the scanner glass plate and properly focused. Furthermore, due to lens astigmatism there might be different optimum focal planes for horizontal and vertical patterns.

7. Colour channels misregistration

   It can be due to positioning errors, and chromatic aberrations of the lens or other optical parts.

8. Geometric positioning accuracy, uniformity, and repeatability

   Of major importance is accuracy. If it is high over the whole scan format and stable over time, then both uniformity of scanning movement and high repeatability are guaranteed. DTP scanners have poor accuracy and uniformity. Their geometric errors are frequently varying.

9. Geometric resolution

   This actually does not refer to an error. However, it is a quality parameter that should be determined and optimised. It can refer to individual components, e.g. sensor, optics etc. However, from a user point view what really counts is the geometric resolution, usually given by the MTF, of the whole system.

10. CCD nonperpendicularity

    If the CCD rows/columns are not parallel/vertical to the scanning direction, then a shear will be introduced. The same will occur if the two scanning directions are not orthogonal to each other. This shear can be accommodated by an affine transformation in the interior orientation.

11. Grey scale linearity

    It refers to the relation between generated electrons in the sensor and output grey values. Ideally this relation should be linear, but with current technology linearity is limited to about 0.5% due to the on-chip amplifier.

12. Dynamic range

    As with geometric resolution, dynamic range is a parameter (not an error) that should be determined and optimised. It refers to the ability of the sensor to detect fine grey level changes and to accommodate images with high contrast. If the latter is not possible, then the grey values are saturated. Since the dynamic range depends on the noise level and this depends on the density, dynamic range should be estimated for different densities. Typically the upper range of the densities is limited, i.e. the scanner can not detect grey level differences in very dark regions. Good sensors have a typical dynamic range of 60 - 80 dB and with cooling and slow scanning 100 - 120 dB can be achieved.

13. Colour balance

    Since CCDs typically have a nonuniform response in the visible spectrum, i.e. in blue the sensitivity is lower than in green and red, proper actions should be taken (e.g. individual illumination, scanning speed, or integration time for each channel) in order to achieve balanced colours in the scanned image.

14. Radiometric accuracy (electronic noise)

    Under this title different noise types are grouped (thermal noise, blooming, smear, tailing, gain/offset of individual sensor elements etc.). Since it is difficult to separate the different noise sources what is usually checked is the uniformity of the photo response (Photo Response NonUniformity) by scanning and analysing the grey values in homogeneous areas. Although the individual error sources are time dependent, it can be generally assumed that the overall radiometric accuracy is stable over time. Noise can be reduced by averaging multiple frames, cooling of the sensor and slower sensor signal integration and read-out speed.

15. Pixel size

    The pixel size may differ from the size implied by the scanning resolution and furthermore it can be different in horizontal and vertical direction. The actual pixel sizes can be estimated by an affine transformation in the interior orientation.

16. Colour purity and other colour quality properties

17. 3-chip linear CCDs

    3-chip linear CCDs (one for each colour channel) are used in photogrammetric scanners. The three CCD lines should be parallel and the distance between the lines should be accurately known and an integer multiple of the sensor element pixel spacing.

B. Frequently varying errors

1. Temporal radiometric variations

   Usually checked by estimating the grey level temporal variation of homogeneous areas.

2. Stripes (L-CCD, ML-CCD)

   Both dark and light vertical stripes can occur due to dark current noise, dark current nonuniformities, different sensitivity or wrong calibration of the individual sensor elements, illumination nonuniformity, dust, and blemishes.

3. Echoes due to multiplexing

   Multiplexed read-out can occur with multiple linear CCDs or with large area CCDs which use multiple read-out to increase the read-out speed. Since adjacent information in the video signal does not refer to adjacent elements in the original image, sharp transitions in the analogue signal may be caused. This can lead to echoes, i.e. repetition of the signal in all multiplexed output (e.g. with ML-CCD repetition of the signal of each linear CCD in all other linear CCDs).

4. Different noise patterns and response between the CCDs (ML-CCD)

5. Vibrations

   Caused by instabilities of the positioning system of the scanner, particularly when the scanning speed is high.

6. Illumination nonuniformity and instability

   Nonuniformity may be due to the illumination source, border effects or the optical parts (e.g. illumination drop-off at the border of the lens). Stability depends on the illumination source and the stability of the power supply.

7. Mosaicking errors (A-CCD, L-CCD)

   They can occur in photogrammetric scanners when combining tiles (A-CCD) or swaths (L-CCD) and may be of geometric or radiometric nature. Since these scanners are geometrically accurate and stable random geometric errors are rather seldom (scanners that use image matching procedures to find conjugate points in overlap regions and thus mosaic the images are more susceptible to errors). Radiometric errors are more pronounced, especially with linear CCDs, and can amount even to several tens of grey values. They are due to different response of the individual sensor elements, missing or incorrect radiometric calibration, or illumination nonuniformity and instability.

8. CCD saturation

   It is related to the dynamic range (see above). Even if the dynamic range of the sensor can accommodate the density range of the image, saturation can occur if the values of the minimum and maximum density of the image are not estimated properly. These values are used to map the sensor output to the grey values, and ideally should be automatically detected by the scanner for each individual image and each colour channel.

9. Linejitter (A-CCD)

   It does not occur with digital CCDs or pixel synchronous digitisation. Its magnitude is generally less than 0.1 pixel.

10. Dust, threads, film scratches etc.

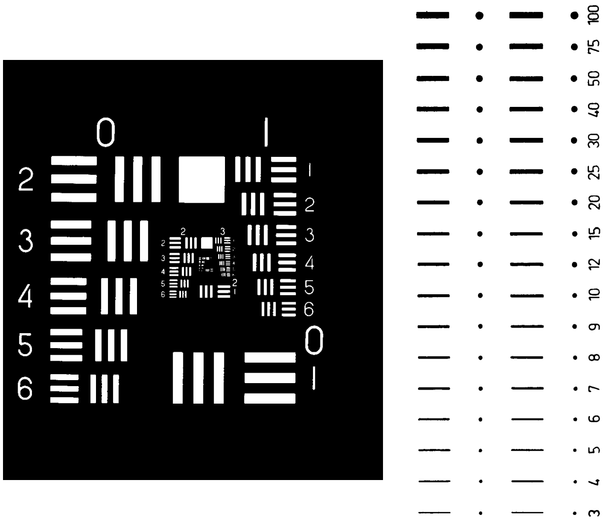
In DTP scanners the errors in CCD direction considerably increase towards the borders of the scanner stage, and in scanning direction they increase slightly towards the end of the scan. As it can be seen from the above, the frequently varying errors mainly refer to the radiometry, whereby frequently geometric errors (geometric positioning) are generally encountered only with DTP scanners. The aim of scanner vendors should be to design, construct and test the scanners in such a way that as much as possible among the previously mentioned errors are eliminated or corrected. Calibration and corrections should be fast and automated, using test patterns and software supplied by the vendors. Some calibration and tests should be executed only once (e.g. after installation), or periodically by the user (e.g. periodic check of the geometric accuracy), or before and during each scan (e.g. radiometric calibration of the sensor elements). Ideally the latter calibrations should be minimised and implemented in hardware to avoid time losses. Any software postprocessing of the images should be avoided.

3. TEST PATTERNS

Here some important test patterns will be presented:

1. Resolution charts

   Resolution patterns on glass plate (positive or negative) with sufficiently fine resolution are commercially available from different companies. The most common are the USAF test plate using 3-bar targets (Figure 1a) and the NBS test plate with 5-bar targets and resolutions of 0.25 - 228 lp/mm and 1-500 lp/mm respectively in steps of ca. 1.12 (both targets have lines in horizontal and vertical direction). 15-bar targets have the advantage that they provide 10 cycles that are not distorted because of being near the ends, and through averaging the MTF can be determined more accurately. Such targets are produced by Itek and Heidenhain (Dr. Johannes Heidenhain GmbH, Dr.-Johannes-Heidenhain-Str. 5, D-8225, Traunreut, Germany) with a resolution of 1 - 1000 lp/mm and 1 - 625 lp/mm respectively in steps of ca. 1.26 (both targets include only vertical lines). Resolutions of 3.6 - 100 lp/mm completely suffice to test scanners with pixel size from 300 dpi to 5 microns, while the most interesting range is 20 - 50 lp/mm. Razor blade edges can also be used to estimate the MTF by employing edge gradient analysis methods. Other patterns that can be used are: (a) parallel groups of n-bar targets ($n \geq 3$) with increasing frequency, whereby n increases with frequency (one such glass plate is sold by Heidenhain), and (b) Fresnel zone plates that consist of concentric rings with radially symmetric, sinusoidal intensity distribution and exhibit a linear relation between local spatial coordinates and spatial frequencies. Important quality aspects of such targets are high contrast, sharp, well-defined



a) b)

Figure 1. Test plates from Heidenhain.

edges, planarity of glass plate, and accurately known line width.

2. Gray scale wedges

   Such patterns are sold e.g. by Kodak and Agfa. Kodak offers the SR37 opaque grey scale wedge (21 x 2 cm) with density range 0.0D-1.8D and 0.05D density steps, and the transparent ST34 wedge (13 x 1.5 cm) with range 0.0D - 3.4D and 0.1D density steps. A pattern containing a larger number of steps can be fabricated in a photographic laboratory and the densities can be accurately measured with a densitometer. A way of producing a grey scale wedge is given by Dam, 1994. The commercially available patterns should also be measured with a densitometer, kept free of dirt, and if they are worn out they should be replaced. Important requirements for such targets is high homogeneity of each density region and accurate knowledge of the density values.

3. Patterns for testing Photo Response Non-Uniformity

   For such tests the previously mentioned grey scale wedges can be used. An alternative is to use a neutral low density object, e.g. the scanner glass plate.

4. Fundamental features

   Since lines and dots are fundamental features in photogrammetric applications, their reproduction (image quality) should be checked by scanning lines and dots of varying size. Such a target (Figure 1b) is produced by Heidenhain.

5. Test charts for tonal and colour rendering etc.

   The UGRA/FOGRA (UGRA/FOGRA, 1988) reproduction test chart is a 20 x 27 cm photograph which can be used for control of tonal rendering, colour rendering, grey balance, image reproduction, and image quality, e.g. defects such as dominant colour casts, improper grey balance, graininess etc. Kodak also sells opaque and transparent patterns (12 x 10 cm) with reference colour table and CMY colour model, and colour separation guides.

6. Grid plates

   Grid plates are used to check geometric aspects (especially accuracy). Typically they consist of grid lines with a spacing of 1 - 2 cm and a thickness of ca. 20 - 40 µm.

7. Grid plates to be scanned together with the image

   Such plates can be used for geometric calibration of DTP scanners. The plate should have geometric patterns at the borders which must be scanned simultaneously with the film (a proposed grid plate is shown in Figure 2). In other cases plates with dense grids are used to be able to find an accurate geometric reference for individual tiles (used in the Vexcel VX 3000 and the Rollei RS1-C scanners). The grid and the film are either scanned together (thus, the grid patterns cover film portions) or they are scanned in two passes whereby in this case the grid patterns do not interfere with the film (principle used in the Vexcel VX 3000 and the RSC camera).

8. Aerial films

   As test patterns high quality black and white and colour aerial films should also be used. The films can be selected such that an average and a difficult case are represented, e.g. medium and high film resolution, medium and high contrast.

Scanner vendors may use additional or similar patterns, or other calibration devices inside the scanner. Other companies that sell different test patterns, even custom-tailored, are Baumert (formerly Mettler) IMT (Industrielle Messtechnik AG, Im Langacher, CH-8606 Greifensee, Switzerland), Teledyne Gurley (514 Fulton St., Troy, NY 12181, USA) and Max Levy Autograph Inc. (220 West Roberts Ave., Philadelphia, PA 19144-4298, USA). Some photogrammetric companies also sell plates with grid lines and 1 - 2 cm grid spacing.

All above patterns, with the exception of the glass grid plates, can be bought at less than 1000 SFr. each. The price of the grid plates varies depending on the quality specifications, and type and density of patterns. A plate with 11 by 11 grid lines and 2 cm spacing may cost 2,000 - 3,000 SFr., while grids with dense

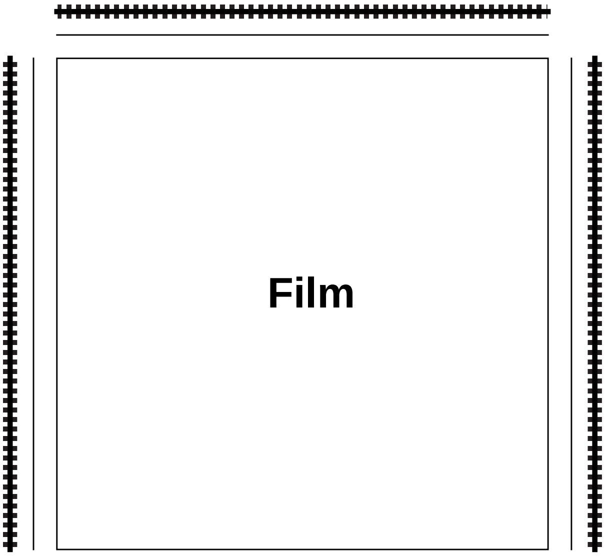


Figure 2. Grid plate to be scanned together with the film in on-line tests for scanners that scan in one or two swaths.

patterns may cost more than 10,000 SFr. An alternative would be to use high resolution stable Estar thick base film, measure the patterns at an analytical plotter, and monitor possible film deformations by occasional measurements. Various patterns can be created using a CAD system, subsequently rasterised and plotted at a high resolution raster plotter. Some precision microdensitometers can also write on films fine, high contrast and geometrically accurate patterns.

Some closer attention should be paid to the grid plates mentioned in 6. and 7. above. Clearly the grid plate should not be larger than the scanning format. A size of 25 x 25 cm is the maximum size that can be accommodated by all aerial film scanners. A border of 1 cm must be left free because patterns can not be fabricated accurately at the borders, i.e. for a 25 x 25 cm plate the useful scan area is 23 x 23 mm. Important aspects of grid plates are the type of patterns used, their position and density, their contrast and geometric accuracy, and the planarity and stability of the plate. Figure 3 shows different patterns that can be used with grid plates (negatives of these patterns could also be used). Patterns D and E are as A and B but rotated by 45 degrees. Circular patterns offer the advantage of isotropy but if the aim is to measure the position of single points, then crosses whose scanned lines are approximately horizontal and vertical are good enough. Several pattern types could be combined in one plate but this would increase the fabrication costs and make the automatic measurement of the patterns more complicated and time consuming. Thus, patterns C and A (the latter possibly with extended lines, i.e. grid lines) are usually selected. The type and size of the patterns must be chosen such that accurate measurement of the patterns (automatic and/or manual) is feasible in both the digital images and directly in the plate to get reference values. Automatic measurement of both dots and crosses is possible with an accuracy of 0.1 pixel or less. Manual measurement in the digital images is usually performed with a haircross cursor and in such a case crosses can be measured slightly more accurately than dots. Measurement of reference values is needed when the fabrication specifications are not reliable or accurate enough, and also for a periodic check of the stability of the plate, and it is usually performed at a comparator or analytical plotter. Again both crosses and dots can be measured accurately. For an accurate automatic measurement of dots and crosses their size (dot diameter, cross line width) should be at least 5 and 3-5 pixels respectively. On the other hand large patterns can not be measured accurately when using manual measurements either in the digital images or at an analytical plotter. If the plates are going to be scanned with different resolutions, then the pattern size must be sufficient (e.g. 5 pixels) for all resolutions. Usually the grid plates should be scanned with the highest scanner resolution, but in some cases, especially for on-line tests (see 7. above), different resolutions will be used. Assuming that the coarsest resolution is 600 dpi, then a 5 pixel target will be ca. 0.21 mm, i.e. too large to be measured accurately by manual methods. To solve this problem either reference values can be determined by other methods than measuring at an analytical plotter (e.g. by a coordinate measuring machine), or a smaller pattern must be included at the center of the dot/cross to permit manual measurements (e.g. a white small dot). A nonisotropic pattern at the corner of the plate permits a unique identification of the patterns independently of how the plate has been positioned on the scanner stage.

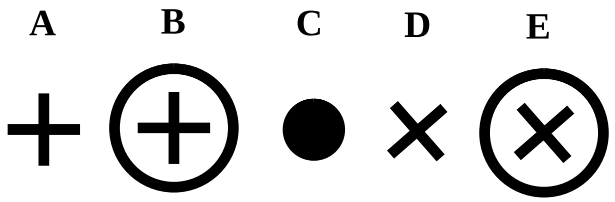


Figure 3. Different patterns for grid plates.

The patterns should cover the whole scanner format that is practically utilised for scanning. Their density depends on the type of errors that should be modelled. A 1 - 2 cm grid spacing suffices for an overall geometric check and modelling of parameters like lens distortion which vary slowly in space. For tiling of area patches at least 2 x 2 patterns should be imaged in each tile, so the required grid spacing depends on the number and size of pixels of the tiles (e.g. for tiles from a 500 x 500 pixel area CCD with 8 µm pixel size, the grid spacing should be less than 2 mm). High pattern density is also required for on-line tests of DTP scanners (particularly in the vertical direction to check inaccuracies and nonuniformities of the positioning mechanism). Depending on the problems anticipated for the given scanner the spacing may be as small as 1 mm (assuming a dot size of 0.2 mm and a 0.2 mm border, the minimum spacing is ca. 0.6 mm). High density is sometimes also desirable in order to have a redundancy and be able to account for inaccuracies in the automatic measurement of the patterns, dust etc.

The glass plate should be planar and have a low thermal expansion coefficient. Typical values for deviations from a plane are 10 µm for a 10 x 10 cm area. Such errors can cause displacements of patterns in the digital image (the displacement is proportional to the radial distance of the pattern from the digital image center and inverse proportional to the product camera constant x scale factor). Typical values of maximum displacements for some scanners are in the 2 - 4 µm range. Thermal expansion coefficients for typical glass qualities result in an expansion of 1.6 µm/K over 230 mm. If the scanner has a temperature that is 10 degrees higher than that when measuring the reference values of the plate, this will result in an expansion of 16 µm over 230 mm or 1.4 µm over 2 mm. This expansion, if it is uniform, will only affect the scale, i.e. the estimated pixel size will be smaller than in reality (for an expansion of 16 µm over 230 mm, the pixel size will be smaller by 0.007%). Plates with higher planarity or quarz plates (with 30 times lower thermal expansion) can be used but at a cost.

4. TEST CONDITIONS AND PROCEDURES

In scanner tests the highest possible true geometric resolution should be used, otherwise some errors are not visible, or can not be quantified precisely. Additionally, for radiometric tests it is useful (i) to choose the density range of the scanner such that errors are amplified, and (ii) use postprocessing functions (gamma corrections, contrast enhancement) again in order to amplify the errors and make them visible. After the errors are detected, their quantification can be based on images scanned under “normal” operational conditions. More errors are revealed using transparent than reflective documents. Problems of the mechanical transport system are revealed better (with the exception of vibrations) at low speeds (the lowest speed is for the highest true geometric resolution and the blue channel).

Necessary precautions like warm-up of the scanner, clean scanner stage and test material etc. should be taken. If the temporal behaviour of the errors is unknown, the tests must be repeated several times. The radiometric performance should be checked for each sensor element. Some of the off-line tests (primarily the geometric ones) must be performed for the whole scan format, different directions, different geometric resolutions, and scanning speeds. The speed can in most cases can not be controlled by the user and is usually related to geometric resolution (the higher the resolution, the slower the speed). Similarly some of the off-line radiometric tests (e.g. radiometric accuracy) should be performed for different densities.

First the radiometric errors should be detected and corrected, and then the geometric ones. The reason is that radiometric errors cause geometric artifacts and reduce the geometric measuring accuracy. Geometric and radiometric corrections from off-line periodic tests should be first applied before proceeding with the correction of frequently varying errors using on-line tests. In all tests automated, fast, and subpixel accurate image analysis techniques should be employed. The techniques should be robust against presence of noise especially dust, threads etc. Dot centres can be accurately measured by Least Squares Template Matching (LSTM), weighted center of gravity, least squares fit of ellipses etc. Centres of crosses can be determined by LSTM, subpixel edge extraction/line following/least squares fit of straight lines/ intersection of two cross middle lines etc. Corrections should as much as possible be implemented in real-time using the scanner hardware (e.g. geometric transformations and grey level interpolation) and the correction values that are prestored by the off-line tests or estimated by on-line tests. In certain cases, geometric corrections need not be applied to the scanned images, thus saving some processing time. Instead measurements in the erroneous images can be corrected by using a table of Δx, Δy pixel coordinate corrections for the whole image format (e.g. a not very dense grid of correction values, whereby corrections at positions between the grid nodes can be interpolated). This table can be computed using the off- and on-line calibration results, and should permanently accompany the image and be used in all subsequent geometric computations.

In geometric accuracy tests the consistency between local and global corrections should be checked, e.g. the parameters of an affine transformation computed from a local and a global grid must be similar after calibration. Instead of using global modelling corrections for all geometric errors, e.g. by a high degree polynomial, it is suggested: (a) to model separately slowly and frequently varying errors, (b) to model the errors in the horizontal and vertical direction separately (especially with linear CCDs), and (c) to model explicitly whenever possible, e.g. the lens distortion, and correct first these errors. In on-line tests, if the scanning resolution is coarse, then only the major errors should be detected and corrected, e.g. when scanning with 600 dpi it does not make much sense to try to detect and correct a 2 µm error. Similarly, in applications that do not require high accuracy, certain calibration tests may be skipped.

The major errors mentioned in section 2 can be corrected by using the patterns of section 3 as follows:

Lens distortion can be estimated together with a test of the overall geometric accuracy using pattern 6. The overall scanner accuracy is given by a conformal or affine transformation using all grid nodes as control points and is indicated by the standard deviation of unit weight of a least squares adjustment. A plot of the residuals can reveal systematic errors or large, random local errors. To analyse the errors locally the same procedure can be repeated for grid meshes or individual rows and columns. In addition, with DTP scanners a local fit will give much better results than a global one. Thus, it is possible to estimate corrections for each individual subregion, reference them to the subregion center and compute the actual corrections at each pixel by interpolation using these values. The practical accuracy that can be achieved should be given by a transformation using only the four corner nodes as control points (as is usually done in the inner orientation of the images) and all the rest nodes as check points. This test should cover the whole usable scan format and be performed for different geometric resolutions. For on-line tests with DTP scanners inaccuracies and nonuniformities in the positioning can be revealed by using the vertical crosses/dots at the borders of pattern 7 (see also Figure 2).

CCD blemishes and radiometric accuracy can be estimated jointly by using patterns 3 or 2 (in the latter case to correctly detect blemishes all sensor elements should image a homogeneous region). Radiometric accuracy should be estimated in sufficiently large regions not including blemishes, dust etc. In addition radiometric accuracy can be estimated for different geometric resolutions and for linear CCDs estimated separately in vertical and horizontal direction. Blemishes can be corrected by substituting their grey level with the average or median of the correct pixels in their neighbourhood. CCD misalignment can be estimated by scanning a horizontal line (e.g. using pattern 6 or 7) and it will be indicated by a broken straight line. The search space of automatic procedures to extract the edges and estimate the amount of misalignment can be reduced by manually given approximations or by an approximate knowledge of the position of the CCD overlap in the scanner coordinate system. This type of error can not be corrected so easily in real time using hardware because it generally requires transformation and resampling in both directions. If the CCDs have parallel direction but are not collinear, then the error can be corrected by a vertical shift of each CCD swath and resampling. For detection of CCD overlap errors straight, high contrast lines inclined by 45 degrees can be used. Again overlaps or gaps will result to broken lines. An alternative is to use one known horizontal distance for each overlap region, e.g. two crosses on either side of the expected CCD boundary (see pattern 6 or 7). Subsampling errors can be revealed by using pattern 4, positioning it in horizontal and vertical direction, and scanning it with different geometric resolutions. The modulation can be computed by averaging grey level profiles vertically to the line direction, and estimating the edge position and the average grey value on either side of the edge. Grey level profiles along the middle of the lines will also show the uniformity of grey levels along the line. Alternatively, a similar procedure with pattern 1 can be used. The rendering of the fundamental patterns can be evaluated by estimating width/ length/contrast of lines (with the lines scanned in horizontal, vertical and two diagonal directions) and size/contrast of dots. Smearing can be estimated by scanning horizontal and vertical lines (patterns 6 and 7) at different scanning speeds/resolutions. The width and the contrast of the lines should be estimated. As a correction a restoration filter in the vertical direction can be applied such that horizontal and vertical lines are similar. Such a filter can be estimated for every scanning speed/resolution and optionally be applied to any scanned image. Focusing can be checked by scanning sharp, high contrast edges. When the image is in focus, the edges have the maximum steepness and the highest contrast. Colour channel misregistration can be estimated by scanning high contrast, straight vertical and horizontal edges. For this purpose patterns 6, 7 or 1 could be used. The patterns should cover the whole scan format. In each colour channel the patterns (edges, corners) should be measured. By matching corresponding features misregistration in x and y over the whole scan format can be estimated.

Geometric resolution can be estimated using pattern 1. The bar targets must be scanned in horizontal and vertical directions (preferably also in the two diagonal ones), with different resolutions/speeds and with DTP scanners at the center and one corner of the scan format. The decision on the finest, still visible, bar target should be based on automated image analysis and selection of a threshold for the modulation, and not on visual analysis.

Grey scale linearity and dynamic range can be estimated by using pattern 2. Only the central region of each density pattern should be used for analysis. The average and RMS of grey levels within each such region should be computed. Dynamic range can be also tested with high contrast aerial images. The histograms of the images reveal the grey level distribution and possible saturation, whereby saturated areas can be easily visualised by displaying grey values 0 and 255 with a colour using a LUT. Testing of colour balance can be performed by using pattern 5. A procedure for such a test is given in Lenz et al., 1994. In scanners that employ automatic density control, pattern 2 could be used to check whether the minimum and maximum density that are estimated by the scanner are correct.

In 3-chip linear CCDs the test whether the lines are parallel and the estimation of the distance between the lines can be performed by scanning one or more parallel horizontal lines over the whole sensor length (see patterns 6 and 7). If the distance between the 3 CCDs is not taken correctly into account by the scanner, then one straight line will be imaged at different, parallel positions in each colour channel. If the 3 CCDs are not parallel, then the imaged line will have a different direction in each colour channel, and the direction difference will give the angle by which the CCD lines are rotated with respect to each other.

Stripes can be detected by scanning a swath over the whole linear CCD length and using a homogeneous object (pattern 3). Discontinuities in horizontal profiles will indicate vertical stripes. It is better to average many profiles, i.e. compare the grey level average of each column with its neighbours. Noise due to dust etc. can be excluded since it results to local grey level discontinuities that do not extend over the whole column. When applying this test on-line while scanning aerial films, the grey level average of each column can again be used but the assumption that neighbouring columns should have equal averages is only approximately correct. Thus, it is better to scan and analyse a homogeneous area, e.g. the glass plate at the top and bottom border of the film. Instead of using only the average the grey levels of each column can be used to estimate an additive and multiplicative correction (gain and offset).

Errors due to multiplexing can be detected by scanning sharp, high contrast edges imaged in each different sensor subarea that is used in the multiplexed read-out. Pattern 6 may be used for this purpose or different patterns that are imaged at the border of aerial films (see Figure 4). This error is practically impossible to be corrected with a posteriori calibration.

Different noise patterns and response between the CCDs (ML-CCDs) can be detected by scanning a homogeneous area. Using the known (or approximately known) position of the CCD boundaries, a central region of each swath can be used to estimate the mean and standard deviation of the grey levels. Different noise patterns can be also visually revealed by scanning a textured pattern, e.g. an aerial image, and subtracting from it a low-pass filtered version of it.

igure 4. Echoes. LK 225 and 6298 coming from the 1st and 2nd linear CCD are repeated in the 3rd CCD (error due to multiplexing). The grey level error is ca. 1-2 grey levels (exaggerated here for better visualisation).

Vibrations in the vertical direction can be detected by using the dense vertical crosses/dots at the borders of pattern 7 (see Figure 2). Vibrations in the horizontal direction can be detected by using the two vertical border lines of the same pattern. The vibrations will cause the straight lines to be imaged as sine curves. The shift in the left and right vertical line should be the same. The lines must not be known, but must have high contrast and be straight. Using image processing the edge points can be detected, a straight line fit can be computed, and the residuals from this fit will give the position and the amount of the errors. These errors can be corrected a posteriori by a linear transformation and resampling in the horizontal direction only for the lines where such vibrations occur.

Illumination nonuniformities can be corrected by scanning a homogeneous area and estimating correction values for each individual sensor element. A good homogeneous area is the same glass plate with which the film is covered. Alternatively, homogeneous test patterns with 2-3 different densities (e.g. 0.0D, 1.0D, 2.0D) could be scanned. To reduce the effect of noise, multiple images can be taken and averaged. This procedure must be performed for each scan, each colour channel, and for single linear CCDs, scanning in multiple swaths before each swath.

Radiometric errors when mosaicking tiles or line swaths can be corrected by application of radiometric calibration and use of stable illumination. Since the latter is difficult to achieve, it is safer, although more time consuming, to scan with an overlap and apply correction procedures similar to those used in mosaicking of ortho-images. When no overlap exists, corrections can still be estimated, although not as safely as when having overlap, by using the border lines/columns and assuming that global grey level statistics between neighbouring border lines/columns should be equal.

Automatic density control can be performed by first scanning the image in coarse resolution and by analysing the histogram a correct minimum and maximum density can be estimated. This procedure should be applied for each individual colour channel.

5. REQUIREMENTS FOR SCANNER VENDORS

Scanner vendors should perform scanner calibration at different stages. Calibration after fabrication of different scanner parts, as well as overall scanner tests that should be applied before delivery from the factory, after installation, service, and significant firmware and software changes. In the latter tests the same, vendor-provided test patterns and programmes should be used. These tests often determine correction and other parameter values that are stored in the scanner and used in each scan. Thus, if these values are wrong, systematic, permanent errors will occur, i.e. the test procedures must be accurate and robust. Each time the scanner is turned on, usually certain parameters are determined (e.g. a home position for the scanner stage). Finally, calibration should be performed on-line before or during individual scans. Such on-line tests include:

- Automatic density control
- Corrections for different sensor element response and illumination nonuniformities
- Scale and focus determination (if they can be modified)
- Radiometric and geometric corrections when mosaicking partial images

In addition to calibration procedures scanner vendors should supply a detailed technical description/specification of the scanner and its components. Tolerances (maximum and RMS error) for possible errors should also be provided. A detailed list of topics that could be included in such a technical description/ specification has been submitted by the author to the OEEPE/ ISPRS Working Group on the Analysis of Photo-Scanners. One of the aims of such a list is also to support the use of common, well-defined terms, common units, and common, or at least well-defined, test procedures. The last point is particularly important since often results are reported (not only by the vendors) without specifying the test procedures and conditions.

6. CONCLUSIONS

Scanner testing and calibration procedures are necessary to achieve a high geometric and radiometric scanner performance. The paper presented general, possibly device independent, testing procedures for high precision, high resolution scanning, referring mostly to flatbed scanners employing linear or area CCDs. It was shown that a significant amount of errors can occur, that they must be comprehensively modelled, and that appropriate test patterns can be used in order to detect and quantify the errors. A major current limitation is the high cost of some test patterns, especially grid plates, and the lack of appropriate calibration software. Test procedures for error detection and correction were presented, and requirements for scanner vendors were proposed. It was proposed to correct first the radiometric errors and then the geometric ones. For detection and evaluation of test patterns, digital image analysis techniques employing automated, fast, and subpixel accurate algorithms should be used. Instead of using global modelling corrections for all geometric errors, e.g. by high degree polynomials, it was proposed to separate the errors in temporally stable and unstable and model them separately. Furthermore, the errors should be modelled separately in each direction (especially with linear CCDs), and whenever possible in an explicit manner, as for example for lens distortion. In photogrammetric scanners, calibration efforts should concentrate on radiometric aspects, especially with on-line tests during each scan. In DTP scanners the poor geometric accuracy is of major concern and it was shown that by using patterns at the borders of the film and on-line tests, a geometric calibration is possible. It is hoped that the OEEPE/ISPRS Working Group on the Analysis of Photo-Scanners will contribute to the definition of an appropriate terminology, a complete list for technical description/ specification of scanners, comprehensive and general test procedures and use of appropriate test patterns. By scanning and evaluating different test patterns at various scanners valuable experience and insight into the scanner problems and performance will be gained.

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