MATCHING TECHNIQUES AND ALGORITHMS FOR SOME BASIC PHOTOGRAMMETRIC PROCEDURES IN THE LOW COST DIGITAL PHOTOGRAMMETRIC SYSTEMS

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ABSTRACT

Two opposite solutions are available on the digital photogrammetric system market: high cost/performance solutions based on sophisticated *ad hoc* hardware (e.g. PHODIS ST by Zeiss, DPW 770 by Leica-Helava, etc.) and low cost instruments based on PC platforms (e.g. DVP by Leica), which offer poor performances and are only suitable for small scale, thematic mapping and educational purposes.

A new class of professional instruments can be foreseen: digital instruments based on standard modular hardware and software, which fulfil the standard map production requirements at a reasonable cost and offer most of the advantages of the digital technique. Such instruments should be equipped by:

- a scanning unit, possibly a low cost DTP scanner
- efficient calibration software that provides the corrected primary data from geometric (and radiometric) distortions
- the possibility of refining the human collimation on the rough level determined by the pixel size, using an efficient sub-pixel matching technique
- an automated DEM production procedure, for further orthophoto creation. The authors have implemented and tested the above mentioned basic procedures, in particular:
- a calibration software for the DTP scanners
- a sub-pixel matching programme, working on line
- an automatic procedure for measuring the DEM heights, based on the VLL (Vertical Line Locus) principle.

The algorithms and procedures are here described in detail and the practical results are shown in terms of quality and reliability.

RÉSUMÉ

Les récentes réalisations d'instruments de restitution digitale offrent deux solutions extrèmes: celles basées sur des machines sophistiquées et coûteuses (par ex. PHODIS ST de Zeiss, DPW 770 de Leica-Helava, etc.) et celles très économiques, utilisant un PC standard (par ex. DVP de Leica), avec des caractéristiques modestes et utilisables seulement pour la cartographie thématique à petite échelle et pour un usage didactique.

On aurait besoin d'une nouvelle cathégorie d'instrumens professionels: des réstituteurs numériques basés, autant que possible, sur un *hardware* et des logiciels standard, qui puissent satisfaire les exigences de production de cartographie à un coût raisonnable et donnant la plupart des advantages propre de la photogrammetrie digitale. Tels instruments devraient être fournis de:

- unité d'acquisition d'images (*scanner*) du type DTP
- logiciel pour la calibration des images du point de vue géometrique
- possibilité d'améliorer la collimation humaine, qui est limité au niveau du pixel entier, avec un efficient logiciel basé sur les tecniques de corrélation sub-pixel
- une procédure automatisée pour la production du Modèle Numerique du Terrain (DEM), pour la production d'ortophotos.

Les auteurs ont réalisé et essayé les fonctions de base de ces procédures, en particulier:

- un logiciel pour la calibration des DTP *scanners*
- un logiciel pour l'auto-corrélation sub-pixel
- une procédure pour la mesure des points du DEM, basée sur le principe VLL.

Les algorithmes et les procédures sont illustrés en détail et les résultats sont décrits en termes de qualité et de confiabilité.

1. INTRODUCTION

In recent years, starting from the second half of the 80's, many researchers and the main instrument manufacturers have dedicated growing attention and resources to digital photogrammetry.

The Kern Co. (today LEICA) exhibited a sophisticated stereoplotter in Kyoto (1988): the **DSP1** *(Digital Stereo Plotter 1)*, with above all the aim of managing SPOT images. The year before, the Helava Inc. presented a digital instrument at Phoenix, USA (1987): the **DCCS** (*Digital Comparator Correlator System*) of an innovative nature, exclusively dedicated to aerial triangulation, carried out with an almost completely automatic measuring procedure.

More recently (ISPRS, Washington 1992) the Intergraph Co. produced a refined Image Station equipped with a high resolution graphic screen, active polarising filter and a high performance RISC computer. Many other advanced projects are now in progress (Leica, Zeiss, ...) and will surely be presented in Vienna in 1996.

These all concern sophisticated and costly systems, based on *ad hoc* designed and built hardware.

Some digital instruments have appeared over the same period, first at scientific Conferences and then on the market, using standard PC hardware of a very low cost, offering poor performances, that are suitable for thematic mapping, architectural photogrammetry and teaching. One of the best known is the **DVP** (*Digital Video Plotter*), developed at the Lavall University of Quebec, Canada and sold by Leica.

Another category of instruments can be conceived: a professional stereo-plotter that fills, in terms of performance and cost, an intermediate position between the two opposite solutions that are already on the market. This instrument should allow one to obtain performances of a satisfactory level for the usual cartographic applications, that can be comparable to that of an analytical plotter. Therefore by using limited cost standard hardware, it should be easy to use and should offer many of the advantages of automation that are of the digital photogrammetric approach.

In order to obtain this ambitious objective, it is necessary to carefully analyse the characteristics of the digital images that are to be treated and, as a consequence, to define the acquisition and processing procedures, the accuracy that one considers necessary and sufficient during the different steps of the photogrammetric process and the configuration of the suitable hardware.

2. LOW COST DIGITAL PHOTOGRAMMETRIC SYSTEM (LC-DPS)

A low cost digital photogrammetric system (LC-DPS) should be assembled using mainly standard PC hardware, that is easily available on the market.
The components are:

- a scanning unit for the primary data acquisition from conventional 9" x 9" aerial photographs;
- a restitution unit for orientation, computer assisted restitution and automatic DEM production. This requires:
  - one (or more) CPU based on a 486 or Pentium processor, large RAM (at least 16 Mb) and convenient peripherals for storing and managing images
  - one (or more) high resolution screens (at least SVGA 15" 1024 x 768 dots).

2.1 Image acquisition

In principle a digital plotter is able to manage any type of digital image, directly acquired from satellites or CCD digital sensors, or obtained from conventional black/white or colour photos by scanning. Let us examine this last approach, that will still remain the most common for several years to come.

The scanner market offers very greatly different solutions. These range from sophisticated scan systems such as the **PhotoScan PS1** (Zeiss-Intergraph) which cost over 200,000 US$ to a cheap A4 DTP scanner, which may cost less than 1,000 US$. With the former, one can obtain perfect digital images from the geometric point of view (± 1 μm) with a density of up to 4,000 dpi (pixel size of 7.5 μm), with the latter, the density is of 300 dpi (pixel of 85 μm) where the geometry of the acquired image must however still be verified (errors of many 1/10's of a millimetre). One, in practice, finds the same enormous difference on the scanner market in term of cost and performances that exists between an aerial photogrammetric camera and a poor 24 mm x 36 mm amateur camera.

Consistent with the general philosophy of a LC-DPS one foresees that the standard acquisition scanner should have medium-low level technical characteristics and price: numerous tests have been carried out with the **UMAX PS 2400X**, an A4 scanner with an optic resolution of 600 x 1200 dpi (up to 2400 x 2400 by interpolation) equipped with an illuminator for scanning slides. The choice of the resolution is tied to the occupation of the memory problem: the number of Mbytes (i.e. Mpixels) corresponding to the digitised images for photogrammetric use with different densities, is shown in Table 1.

dpi	Pixel size Δx=Δy [μm]	Mbytes for b/w or 8bit color (9"x9")	overlap area 6"x9"	Mbytes for b/w or 8 bit color (2"x2")	24 bit color
300	85	7.3	4.9	.4	1.1
600	42	29.2	**19.4**	1.4	4.3
1200	21	116.6	77.8	5.8	**17.3**
2400	10	466.6	310.0	**23.0**	69.1

Table 1 - Digital images of different densities. The recommended values for a LC-DPS are in ***bold type.***

As a first hypothesis, considering the performances of a 486 or Pentium PC in terms of speed and of available mass storage, let's limit the size of each digital image to about 20 Mbytes: the standard scanning density should therefore be 600 x 600 real dpi (not interpolated) corresponding to a pixel dimension of about 40 μm. For the small format images used in close-range photogrammetry, the density can also reach 1200 or 2400 dpi, using the interpolation firmware of the scanner during the acquisition stage.

As a conclusion, the standard performances of a LC-DPS should be foreseen for (see Table 1):

- 230 mm x 230 mm (9" x 9") aerial images, that are limited to the 150 mm x 230 mm (6" x 9") overlapping area:
  - black/white or 256 colours (8 bits), 600 dpi
- 60 mm x 60 mm images (such as ROLLEI, about 2" x 2") for terrestrial applications:

- black/white or 256 colour (8 bits), 1200 or 2400 dpi
- true colour (24 bits), 1200 dpi.

One should note that the SVGA 15" monitor of a PC has a resolution of 1024 x 768 pixels and a size of about 12" x 9". The density of the displayed image corresponds to about 85 dpi (pixel of about 300 μm). Therefore, if one represents the pixels of the digital image in screen pixels in the ratio 1:1 (that is a pixel on the screen corresponds to each pixel of the image, without loss of information) one obtains a representation with the enlargements shown in Tab 2.

The images are therefore observed without any optic aid, with an enlargement that is usual for the operator: 7x in the case of photographs scanned at a 600 dpi density (aerial photographs) and 14x if the density is 1200 dpi (ROLLEI photographs).

dpi of the original image	Enlargement on a 15" SVGA screen	Displayed window on the full screen [mm x mm]
300	3.5 x	87 x 65
600	**7 x**	**43 x 33**
1200	**14 x**	**22 x 16**
2400	28 x	11 x 18

Table 2 - Enlargement and portion of the original image displayed in ratio 1 pixel = 1 pixel

2.2 Calibration of a DTP scanner

The wide use of the hard-copy scanning process to generate digital images from traditional photographs has led the researchers to evaluate the geometric and radiometric performances of scanner devices. An OEEPE working group, co-ordinated by Prof. Kölbl [2], has considered the radiometric performances of the photogrammetric scanners, while other researchers from different Universities are evaluating other aspects such as geometry, repeatability, etc.

The geometric errors can be due to:

- CCD sensor misalignment (in the case of three pass scanners), that causes shifting between the bands;
- vibration along the horizontal axes;
- optical distortions;
- acquisition discontinuity due to the buffer capacity;
- non-constant geometric resolution along the two axis.

By comparing the radiometric and geometric results of a consistent sample of acquisitions with the calibrated grey wedge and reseau, it is possible to define a complete model of calibration that must be applied to each digital image produced by the scanner.

The geometric calibration model is determined by the following procedure:

- acquisition of a calibrated grid;
- autocorrelation by pattern recognition techniques of the crosses (fully automatic): a reference target has been defined (see fig. 3) and used for searching the scanned crosses on the grid, by means of the usual pixel and subpixel matching techniques;
- computation and storage of the discrepancies between the co-ordinates of the original grid and those of the acquired image.

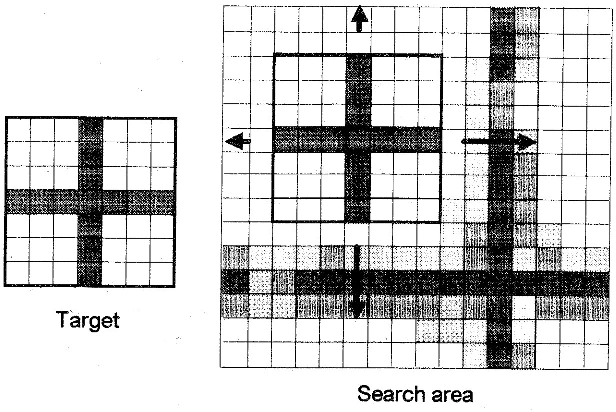

Figure 3 - Target and search area for reseau calibration

The so acquired data are used to correct, in real time, the co-ordinates of a collimated point by means of a bilinear interpolation inside each square mash.

3. DIGITAL RESTITUTION UNIT

The digital restitution unit consists of a high performance PC and screen such as that described in 2., equipped with a system for the 3-D collimation of stereo-pairs and of a dedicated software for orientation and restitution.

The software is performed in order to use human stereoscopic collimation only for an approximate solution at the pixel resolution, this being useful for the automatic refinement of the collimation (see 3.1) or in order to solve some particular cases where the digital algorithms do not find a consistent solution (see 3.2).

The stereoscopic view is automatically controlled; therefore collimations, in the relative orientation phase, give the measurements of both the x and y parallaxes and, in the absolute orientation and restitution phase, collimations only measure the x parallax.

3.1 Computer assisted collimation

During the orientation and restitution phases, all the required points are collimated by the operator, who locates entire homologous pixels with a possible error of 1÷2 pixels.

When the registration command is sent by the operator, the software checks the correct collimation at pixel resolution and then computes a sub-pixel correlation. A target window of 9 x 9 pixels from left image and a search window of 9 x 15 pixels from right image, centred on the homologous pixels previously defined, are used in this phase.

If a pseudo-normal scheme is adopted for taking images, the extraction of search and target windows can avoid the epipolar geometry. In fact, if ω, φ, κ are $\leq 5°$, the relative tilt between the epipolar lines can be neglected.

If *a* is a geometric shift equal to a fraction of the pixel (in the search area)and *b* and *c* are the density gain and shift in the target area, an equation for each pixel can be written as:

$$b \cdot g_1(x) + c = g_2(x+a) \qquad (1)$$

If the image is b/w, a system of 81 equations of this type can be written in the three unknowns *a*, *b* and *c*. If the image is coloured, 81 equations for each RGB colour have to be written. The geometrical shift *a* is the only unknown used, including its r.m.s.e. The solution is computed by using the least square method.

In numerous experimental tests it has been proved that this sub-pixel matching gives an accuracy of positioning that is 0.1÷0.2 pixel: therefore the values of p_x (and p_y if a bi-dimensional matching is carried out) can be determined with an accuracy that is similar to that of an analytical plotter, even in the case where a poor image resolution of 600 dpi is used.

3.2 DEM automatic extraction

A very useful feature of a digital restitution unit is the possibility of automatic data capture for a DEM grid.

When using oriented images, this topic can be achieved using the VLL (Vertical Line Locus) correlation algorithm. A number *n* of equidistant horizontal planes, spaced at a given ΔZ, are defined for each point of the regular grid centred on an approximate value Z_{01} (for ex. the height of the previous determined point). Each point $P_i(X,Y,Z_i)$ is then projected by means of collinearity equations and homologous windows are defined in each image. A correlation coefficient for each pair of windows is then computed. The Z value corresponding to the maximum measure of correlation represents a more approximate value of the unknown height.

The shape of the windows has been defined as follows: 25 x 25 pixels on both images, where different weights are given to each pixel depending on its position.

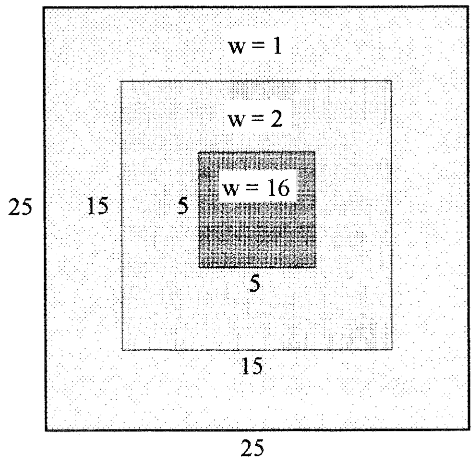

Figure 4 - Weighted window

If the resolution is 600 dpi, the total window size is about 1 mm^2 on the image. This window has been subdivided in three different frames: the weight of the pixels in the innermost frame (5 x 5 = 25 pixels) has been fixed = 16, in the second frame (15 x 15 - 25 = 200 pixels) the w = 2 and in the external frame (25 x 25 - 225 = 400 pixels) the w = 1. This means that each of the three frames have an equivalent total weight (see fig. 5).

The Z co-ordinate corresponding to the highest correlation coefficient is assumed as the new approximate height Z_{02}. The same number *n* of horizontal planes, but now spaced at $\Delta Z/2$ are centred up and down the new value of Z_{02}. An iterative procedure is performed until the distance between the horizontal planes reaches a prefixed value Δh. The last so found Z is assumed as the height of the X,Y point.

If the highest correlation coefficient of the last iteration is not acceptable (for ex. $r < 0.7$ for b/w images or $r < 0.7 \times 0.7 \times 0.7 = 0.35$ for colour images), the software asks the operator to confirm the solution. In both cases a sub-pixel correlation is finally made, following the procedure described in 3.1, in order to refine the height measurement.

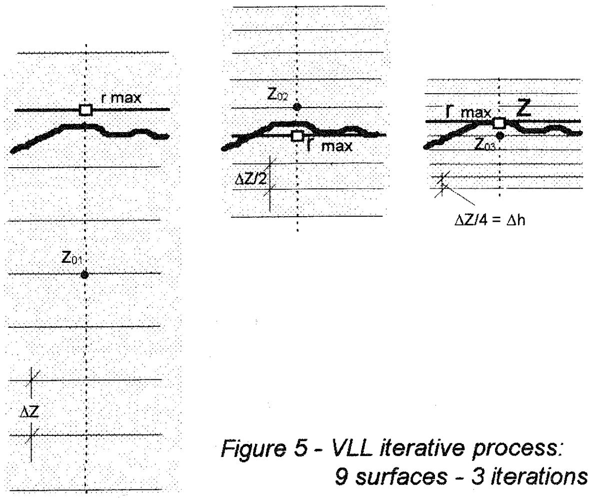

Figure 5 - VLL iterative process: 9 surfaces - 3 iterations

4. PRACTICAL RESULTS

4.1 Primary data calibration

A calibration grid, obtained using a contact copy on film from a high precision glass plate, has been used for calibrating the UMAX PS2400X scanner.

The grid of 10 x 10 square meshes, 20 mm x 20 mm each, has been checked on an analytical plotter, in order to define any deformations due to film shrinkage. The values of the newly measured co-ordinates have been used as "true" co-ordinates for calibration.

The grid has been scanned several times, in order to check the repeatability of the scanner. The results have shown that:

- the scanner must be "heated" for at least 1 hour before using it for scanning. In fact, during the first hour the geometric changes are not negligible: differences are of more than 2÷3 pixels (~ 1/10 mm) along the side of the grid (200 mm) in the X direction, i.e.

along the sensor bar. The stability in the Y direction (driven by stepping motors) is good from the beginning;

- after 1 hour, the repeatability is very good, both from geometric and radiometric points of view. A test on 4 acquired images has shown differences of less than 2 grey levels. The geometric changes are less than 1 pixel;
- however, the (already stable) geometric results are **very bad** in the X direction: discrepancies greater than **900 μm** (!) can arise and their distribution is **not linear**. **It is impossible to use scanned images without differential calibration.** The Y co-ordinates are much better (discrepancies ≤ 1 pixel along the Y grid side).

As already described in 2.2, a calibration based on bilinear transformation has been carried out. The calibration programme, in C++ language, takes a few seconds to determine the 800 transformation parameters of the 100 grid meshes and the 800 parameters of the inverse transformation, which are necessary for an automatic on-line calibration in real time of all the image points collimated during the restitution.

4.2 Collimation of single points

In a conventional LC-DPS the accuracy in the collimation of single points is actually limited by the resolution of the system, determined by the pixel size.

Let's consider a pair of photos in scale 1:S = 1:10,000 (suitable for producing a map in scale 1:2,500) acquired at 600 dpi, that is, with a pixel size of 42 μm. If the operator carries out the collimation in a traditional manner, entrusting the location of homologous points to his stereoscopic vision he will locate for each pixel on the left image its homologous with an accuracy - in the best hypothesis - of ± 0.5 pixel, that is $\sigma_{px} = \pm 21 \mu m$.

It is well known (for ex. [1], p. 41 onwards) that, in the case of normal taking, the r.m.s.e. of the Z co-ordinate is given by:

$$\sigma_Z = \pm S \frac{H}{B} \sigma_{px} \qquad (2)$$

where H is the flight altitude and B/H is the base ratio. In our example, having supposed that the camera has a focal length c = 150 mm, H is equal to 1500m and given a 70% overlapping, B/H = 1:2. Therefore $\sigma_Z = \pm 40$ cm.

This accuracy of heights is low, if compared to that of any analytical plotter (where $\sigma_Z \leq H \cdot 10^{-4} = \pm 15$cm.) and it depends exclusively on the precision of the measurement of the linear p_x parallax. One should note that the planimetric precision (σ_X and σ_Y) is determined, **not** by the **position**, but by the **size** of the image pixel. With the assumed value of 40 μm, the planimetric precision will be, in the best hypothesis, of ± 20 cm, which is a value that can be considered sufficient and whose improvement can be obtained only with a greater scanning density.

If one wishes to be certain of improving the correct location of the homologous pixel, one can adopt the matching techniques, as already described in 3.1.

4.2.1 Points of a "calibration model". Calibration of traditional analogue or analytical plotters was carried out by reconstructing an "artificial" calibration model, obtained from two calibration plates of the already described type. A similar procedure can be used for checking an LC-DPS.

The stereo-pair consists of two identical copies of the calibrated grid, as obtained in 4.1. As an example, by simulating a 60% overlap, a 150mm focal length and a 1:5,000 photo scale, a "flat" model can be reconstructed simply following the usual orientation procedures.

Three cases have been tested:

a) a rough approach: no calibration of the images, human collimation of the homologous crosses (as could be obtained by a non expert operator using a DTP scanner as it is and an existing LC-DPS)
b) a more accurate method: calibrated images (this also simulates a high quality digital image, for ex. as obtained by using a PS1 scanner), but human collimation, to locate homologous entire pixels, is still necessary
c) a computer assisted procedure: as above, but correlation is obtained by using a sub-pixel matching algorithm.

All crosses of the 7 columns (11 rows) of the grid model have been measured, for a total of 77 points for each test. The results (for case c) are summarised in the histograms of fig. 6.

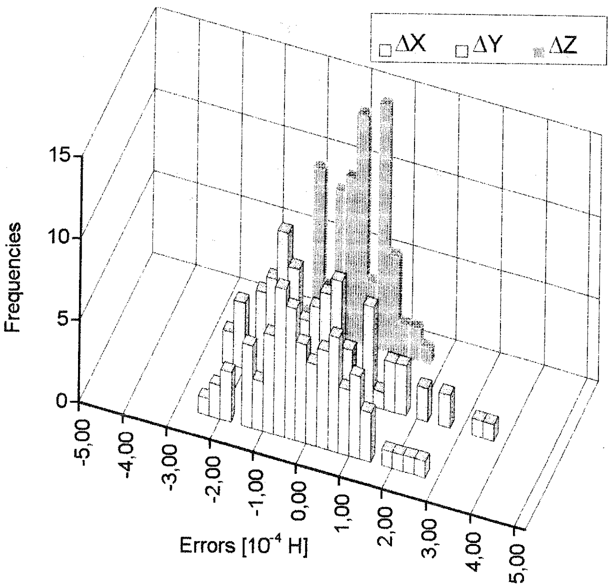

Figure 6 - Relative errors in X,Y,Z on a grid model

In the a), b) and c) cases the relative Z errors (ΔZ/H) have the following m.s.e.:

a) $\sigma_Z = \pm 5.3 \cdot 10^{-4}$ H b) $\sigma_Z = \pm 2.0 \cdot 10^{-4}$ H
c) $\sigma_Z = \pm 0.6 \cdot 10^{-4}$ H

Considering that similar tests on analytical plotters give $\sigma_Z = \pm 0.5 \cdot 10^{-4}$ H, it seems that the last value can be accepted as being very satisfactory. On the contrary, case a) gives unacceptable results, and case b) is also critical for the most standard requirements.

4.2.2 Points of a "real model". A stereoscopic model formed by two colour images at the average scale of 1:4,000 over the town of Ferrara has been used. About 50 points have been surveyed using a DIGICART40 analytical plotter and measuring their *analytical co-ordinates*. The images have been digitised at 600 dpi and the same points have been measured using the mixed procedure as explained before: a rough human collimation at pixel resolution (with an on-line geometric calibration) and an automatic refinement of the collimation at sub-pixel resolution, finally give their *digital co-ordinates*. The average r.m.s.e. of the sub-pixel correlation is 6μm (i.e. 0.19 pixel). Discrepancies between the analytical and digital co-ordinates, expressed in cm, are shown in fig.7. The standard deviation is $\sigma_{x,y}=\pm 9$ cm and $\sigma_z=\pm 5$ cm.

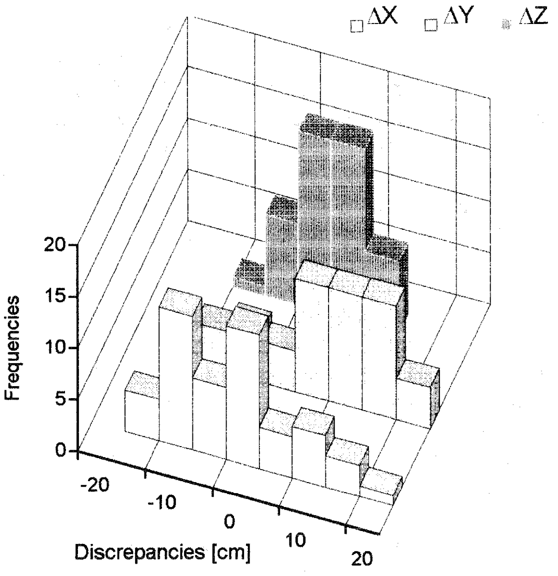

Figure 7 - Discrepancies in single point collimation

4.3 Automatic DEM production

A DEM of 250 points covering rural and urban areas, regularly spaced in 10 m in X and Y, has been surveyed on the model of Ferrara described above, with the DIGICART 40. The same DEM has then been automatically measured by the VLL algorithm as described in 3.2.

Each iteration used 9 horizontal planes centred onto the approximate Z-value. The first distance between the planes was ΔZ = 2m and the last $\Delta Z = \Delta h$ = 2cm (8 iterations). 78,6% of the points have been automatically and successfully measured without any human intervention (*green points*). The remaining 21.4%, where the *r* coefficient is too small, have been marked in red or yellow and required a further operator intervention: 4% resulted to be already correct and 17.4% needed a new collimation. The computation speed is approx. 28 pts/s.

The discrepancies between the analytical and digital co-ordinates of the green points, expressed in cm, are shown in fig. 8. The standard deviation is $\sigma_z=\pm 8$ cm.

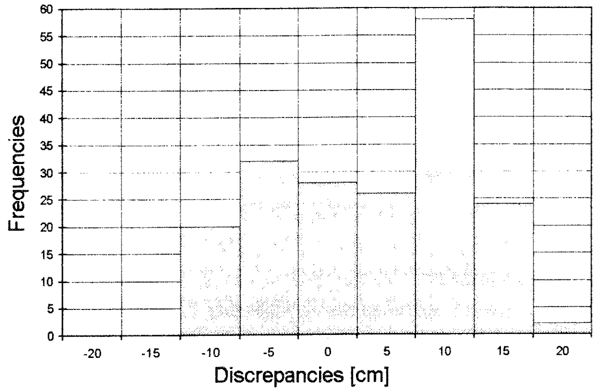

Figure 8 - Z discrepancies in DEM automatic data capture

5. CONCLUSIONS

Performances of an LC-DPS, where DTP scanned images (600 dpi) and human collimations at 1 pixel resolution are frequently used, can be significantly improved if a rigorous geometric calibration of the digital images is carried out and if matching sub-pixel algorithms are applied during the restitution phases.

By comparing the Z measurements on an artificial "grid model", it results that σ_Z changes from $\pm 5 \cdot 10^{-4}$ H (non calibrated images) to = $\pm 2 \cdot 10^{-4}$ H (calibrated images), up to = $\pm 0.6 \cdot 10^{-4}$ H in the case of sub-pixel automatic correlation. This last accuracy is comparable with that obtainable by an analytical plotter.

Practical tests on a real model (colour images at scale 1/4,000) confirm such results when observing both single points manually and a DEM grid by an automatic procedure.

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