THE TRIADIGIT PROGRAM FOR AUTOMATIC AERIAL TRIANGULATION

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Commission II, Working Group 8

KEY WORDS: Photogrammetry, Automatic Aerial Triangulation, Automation

ABSTRACT

The paper presents an Automatic Aerial Triangulation software developed at Dept. I.I.A.R. of the Technical University of Milan in cooperation with the Dept. of Civil Engineering of the University of Parma. The software works on multi-resolution images and performs the selection, measurement and recognition of the tie points in a photogrammetric block. After a short review of problems and perspectives in the AAT, the paper describes the program structure and discusses the results of its application to a test block.

1. INTRODUCTION

Many research groups and software companies have been pushing the development of AAT programs in recent years; the first programs have been released in mid 1990 (Tsingas, 1994; Krzytek et al., 1995, Schenk, 1995; Heipke, 1996; Honkavaara and Hogholen, 1996). The relative delay with respect to other issues in digital photogrammetry is twofold. First, only recently have the development in hardware components made it economically and technically feasible to handle the amount of memory required by the digitization of a whole block of images. Second, analytical plotters still offer a good performance if coupled with trained operators, therefore companies may be reluctant to discard such assets without a clear gain in productivity.

The complete automation of AT would require the identification and the measurement of the fiducial marks; the selection and the transfer of the tie points; the identification and the measurement of control and check points; the computation of initial values of the unknown parameters and object point coordinates (if necessary); the block adjustment, including gross errors detection.

Virtually all methods use image pyramids to reduce the sensitivity to initial values; most apply area-based correlation methods to perform or to refine point measurement.

The relative vulnerability of the matching techniques to gross errors, which may amount to a large percentage of the observations, demands robust methods and high redundancy. In the long term, it may be foreseen a trend towards a standard block configuration with 60% overlap in both direction, with benefits in accuracy and reliability of all subsequent photogrammetric operations.

Automatic localization and identification of the fiducial marks (Heipke, 1996) should be insensitive to film type, pose of the photograph on the scanner stage, image quality (noise), camera model, etc; often, methods track the fiducials down the image pyramid using level-appropriate templates.

Tie point selection is mostly performed using feature extraction methods. To begin point transfer, depending on the true automation level of the program and on the robustness of the method, auxiliary information may be supplied (indeed, should the use of GPS and INS navigation systems become commonplace, this problem will fade out).

Some programs use feature-based matching, less dependent on knowledge about exterior orientation, to compute a relative orientation between adjacent pairs; on the other hand, if the actual flight path differs markedly from the plan, some interaction may be still necessary. Accurate information on the external orientation allows to effectively use the epipolar constraint in the search for correspondences, with benefits in computing time and reliability.

Still basically unsolved is the identification and measurement of control and check points (Guelch, 1995), either artificial (signalized) or natural; strategies have been proposed and implemented for targets or predefined object shapes (corners, roof edges, etc.) (Foerstner, 1988; Dal Poz, 1996). Much more complex is to try to recognize generic control points, which are often only known by sketches: therefore the operator's intervention is still necessary.

The strategy for tie point transfer is usually repeated, maybe omitting some steps, within all the pyramid levels. At each level, a block adjustment may be performed, improving the knowledge of the exterior orientation and discarding false matching.

Overall, the degree of automation, with adequate hardware resources, is high. Processing time may be considerably smaller than that taken by an operator; further savings may be gained in the plotting stage, since inner and relative orientation are stored in the computer and can be retrieved without re-measuring. Accuracy and reliability of results depend to some extent on image scale and texture: indeed, while the performance is generally good in flat and textured areas, large scale images in city centres may still give rise to problems, if an area-based method only is applied. To gain a deeper understanding of the problems and to compare strategies, several tests have been organized. In this paper we describe the concept of the AAT program TRIADIGIT, jointly developed by the TU of Milan and the University of Parma and we report about the results of the program on a small scale block.

2. PROGRAM STRUCTURE

The AAT program TRIADIGIT performs tie points selection, measurement and transfer within a photogrammetric block, based on some a priori information (mainly the exterior orientation, the mean terrain elevation and the maximum height difference in the area). The program, still under development, runs under Linux operating system and still lacks several basic tools (especially user-friendly interface, visualization of the matching process as well as tie point selection, to visually evaluate the actual behaviour of the algorithm if desired; moreover, there are no tools for the interactive measurement of points). Other features, designed to increase flexibility, are still unimplemented: therefore many stages are still performed interactively. Images may be input as RAW data or in BMP format; the program runs in batch mode and outputs image and (approximate) object coordinates of tie points. In the current release, it does not execute any block adjustment at each level of the pyramid, therefore there is no improvement of the exterior orientation in the procedure; besides, the outlier rejection is based on very simple test: therefore a subsequent block adjustment must take care of both tasks.
As it is, the procedure starts by selecting points at the highest level of the pyramid. Their number can only decrease or stay unchanged in the lower levels, depending on whether the similarity measures and consistency checks are satisfied. This may prove a limit and could be removed in a later program release; nevertheless, in the light of the experience gained up to now, it doesn't look a major drawback.

2.1 Data preprocessing

The data and the values of some auxiliary parameters are prepared by specific programs; at the current system development stage, interaction is necessary to determine the interior orientation and approximate values of the exterior orientation.

2.1.1 Image pyramid generation
The strategy adopted is based on multi-resolution images. The number of levels in the pyramid depends on the texture content and on the geometric resolution of the images: in our (however small) experience we found 5-6 levels adequate for pixel size around 20-25 micrometers. The batch process runs in two stages, by filtering with a gaussian 5x5 mask and resampling with a decimation step of two.

2.1.2 Feature point extraction
The selection of image features likely to become tie points is performed by the Förstner operator (Förstner, 1986) applied to the images of the highest level (i.e., those with the lowest resolution).
Pixels are discriminated based on the roundness (which must be greater than 0.5) and on the local maxima of the interest value. As far as the search window size is concerned, we didn't perform any systematic testing to find out whether an optimal size exists. For large scale and medium resolution images we adopted a window size of 15 pixels, while with medium scale blocks (1:40000) we found adequate a window size of 11 pixels.

2.1.3 Pixel to image transformation
The fiducial marks are measured by template l.s.m. in the zero level of the image pyramid, by using artificial templates. Their approximate position is given interactively by the operator, which also takes care of the correct labelling of the marks. In the near future this step will be performed by a batch program, which is currently in an advanced development stage.
An affine transformation from the two sets of points is then computed with the L1 norm and the transformation parameters are stored in files for later use.

2.1.4 Approximate values of exterior orientation
The search for homologous points is directly performed on the whole block, using a bundle approach, without forming independent models and computing relative and absolute orientation. Therefore, good initial values are necessary to limit the search area and to ensure a certain likelihood that tie points can be found in more than a pair of images. The program accept as reference system that given by the control points or a conventional reference system. In the former case, projection centres and strip directions (given by the κ angle, drift is neglected) are derived by GPS or from the flight plan, while ω and ϕ are assumed to be zero. In the latter case the system is parallel to the image coordinate system of an arbitrarily chosen reference image, under the assumption of dealing with nadir images. The image reference systems of the other photographs are tied to the first by computing simple shifts or plane Helmert transformations based on the interactive measurement of one or two pairs of image points. This approach has worked reasonably on the small blocks we have dealt with in the test phase, but may become impractical on larger blocks.

2.1.5 Program options and control parameters.
The program may work on the whole block or in subareas, defined by the image numbers, and with any number of levels in the pyramid. Standard corrections to image coordinates (distortion, refraction, earth curvature) may be applied. To control the matching process, the window size of the l.s.m. (the same in all levels) is specified, together with the threshold for the correlation coefficient and the maximum change of the shape parameters of the affine transformation.

2.2 Tie point matching

The search for correspondencies begins at the highest level of the pyramid. Each interesting point selected by Förstner operator is back projected on all images, based on the available a priori information on the exterior orientation and the DTM. The terrain is simply represented by a horizontal plane, but it is also possible to include any available information on elevations, such as a DEM. A window in image space is then computed around all approximate positions, whose size Δp depends on exterior orientation and DEM uncertainty:

$$\Delta p = 2 \cdot [c \cdot B + \rho_1 \cdot \Delta Z_0] \cdot \Delta H / Z^2$$

where:
c = principal distance;
B = base length;
ρ_1 = image point distance from PP;

ΔZ_O = height difference between the pair of projection centres;
ΔH = maximum ground elevation;
Z = mean relative flight height.

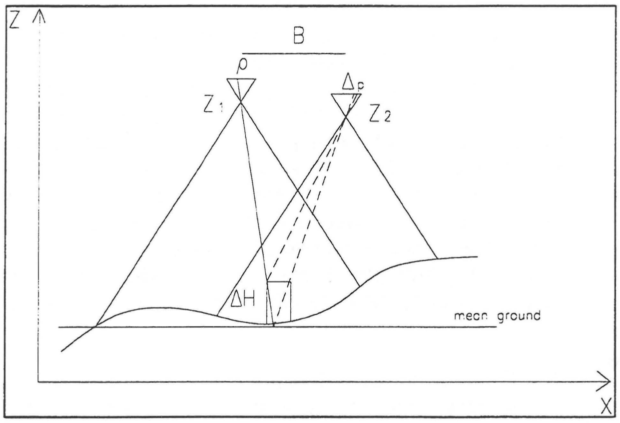

Figure 1 - Results of ground height variation on search window size

Currently the uncertainty on the exterior orientation is accounted for by increasing the value of ΔH (see Fig. 1). All interesting points in the window are compared with the template by a l.s.m. with an affine model: the assumption is that a relatively high percentage of the interesting points are actually the same or anyway have been selected within the convergence radius of the l.s.m. The larger the search area, the larger the probability of identification errors, especially in large scale blocks in urban areas.
The process goes on for each point in each image, looking for in all images where conjugate points may be found. Therefore it may happen that tie points are selected very close to each other, because each image becomes in turn the reference image and therefore its points become templates. Once processing in the first level has been completed, a coarse gross errors rejection is performed (see 2.2.1), before moving to the next level. The remaining points are transferred to the next level by simple multiplication of their coordinates by the decimation factor and the above described procedure is repeated, but starting only from the points accepted as good: those discarded in the previous levels are definitely kept out; the rationale is that subsequent matchings simply refine an initial correspondence at a higher resolution and may discard false correspondences (small gross errors). Apart from the previously computed position, four more starting position for the matching can be selected in the surroundings, to account for the increased resolution. It is also possible to apply again the interest operator in the area, to find the best local candidate. In Fig. 2 the position of two corresponding points is shown within all image pyramid levels; images refer to photogrammetric block "Piemonte" which has been considered for the test described in the following (see par. 3)

2.2.1 Gross error rejection
The search for conjugate points by stereo image correlation does not include geometric constraints, since the information on the exterior orientation is too weak. In order to identify inconsistencies among tie points, *x* and *y* parallaxes are computed, under the hypothesis of quasi nadir images, approximately flat terrain and negligible relative κ rotation between the pair. For each pair of images that share a minimum number of tie points, the corresponding *x* and *y* image parallaxes are computed and two robust location and dispersion measures are computed: the median *me* and the median of the absolute values (*mav*) of the residuals with respect to *me*. If the measured parallaxes are outside a symmetric acceptance interval centred on *me*, the coordinate pair is rejected. The endpoints of the interval are given by $me \pm \alpha\ mav$, where the coefficient α is set to 3 in all but the last level, where it is set to 2.
It is apparent that the discrimination power of the test is maximum in flat terrain, while it sharply decreases with terrain roughness (as it happens not only in mountain areas, but in large scale images of towns). Even in case of flat terrain, if there is a significant relative κ rotation between the images, as it happens especially between adjacent strips, the test is not much worth: the relative rotation and perhaps a scale factor should therefore be estimated, again with a robust method.

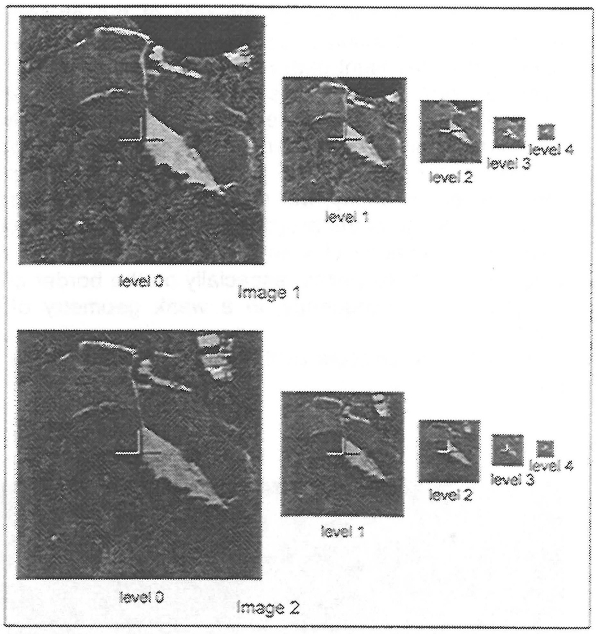

Figure 2 - Position of two corresponding points in the image pyramid of block "Piemonte"

3. PROGRAM TEST

The program TRIADIGIT has been firstly applied to the photogrammetric blocks of the 1997 OEEPE/ISPRS test on evaluation of tie point extraction in digital aerial imagery. These blocks were delivered without ground control points and so we could check the quality of these results only by the sigma naugh of a l.s. bundle adjustment.
For a further and more significant test we considered another block, flown in May 1995 over a hilly area in Piemonte (Northern Italy) by CGR-Parma to check the performances of the GPS ASCOT system. The whole block "Piemonte" is made up of 24 images at a mean scale of 1:40000 and with standard overlap (60% forward

and 20% sidelap). The block was adjusted by CALGE program with a standard ground control and the final results, in terms of sigma naugh, summed up 8.5 μm. In Fig. 3 the typical image texture of "Piemonte" block is depicted.
The new test with TRIADIGIT was carried out with only 10 images, shared into two five-images strips. Imagery digitization was performed by a PS1 scanner in the CGR laboratory in Parma at a resolution of 28 μm.
Inner orientation was computed by the semi-automatic procedure described in 2.1.3. Images were acquired by a RC30 Wild camera, which has two kinds of fiducial marks; therefore, two diverse templates were used. Thanks to the absence of noise nearby the fiducials, measurements turned out to be accurate; (σ_0 of the robust adjustment - L1 norm - computed from the affine transformation from pixel to image coordinates was on average ± 6.6 μm (thus 0.24 pixel size).
Four levels of the image pyramids were built (a resolution 16 times smaller the original one). Interesting points were extracted by Förstner operator from the zero level images, with a window size of 11 pixel. On each image a mean value of 700 points were chosen, evenly distributed.
Another preliminary task was the computation of approximate exterior orientation parameters of the photogrammetric block. Coordinates of projection centres were calculated from the flight path known by means of GPS. We assumed zero value for pitch and roll, whereas determination of yaw was performed by measuring interactively two corresponding points for every couple of overlapping images in the block. This procedure turned out to be rather time-consuming, but necessary at the current development stage of the program for a correct execution of AAT. Approximation of κ angle by more than $1 \div 2^9$ may result in lack of tie points, especially on the border of the images and, consequently, in a weak geometry of the block.
The control parameters of the program were set as follows:

- *ground model:* horizontal plane;
- *max. elevation difference:* ± 200 m;
- *image coordinate corrections:* radial distortion;
- *l.s. matching window size:* 21 pixel;
- *threshold on the correlation coefficient for good matching:* 0.75.

The AAT execution required about 9 hours on a PC equipped with a P200 Mhz processor.
Tie points found by the program add up to 2654, corresponding to 12786 photogrammetric observations, with a mean of 2.4 rays for every point. Table 4 shows the number of tie points found at every level of resolution. From a stage to another a consistent number of points were thrown out, in part because of bad matching and in part due to the blunder rejection criterium used.
The photogrammetric block was then adjusted by a least squares procedure (CALGE program); two stages were performed:

1. firstly, a bundle adjustment with minimum constraint to detect the outliers. At the end of this first stage 336 out of 2654 points were eliminated (12.6%); the sigma naugh was 13.0 μm (Table 5 shows the adjustment results);
2. second, the computation of the exterior orientation was carried out by using 5 natural ground control points, directly measured on the digital images. Unfortunately, these points could not be measured with sufficient accuracy, due to the uncertainties of their definition in the sketches and the large pixel size; hence the final result of this orientation was retained as not satisfying.

Finally, the exterior orientation of the block was computed by constraining 7 projection centre coordinates derived from the adjustment of the measurements made at the analytical plotter.

Figure 3 - Typical image texture of "Piemonte" block

This step was performed in order to compare the results obtained by TRIADIGIT with those of the to analytical plotter.

In Fig. 6 a general view of "Piemonte" block is depicted, showing the points found (represented by a little circle) and those refused after outlier rejection.

3.1 Analysis of results

Object coordinates of the tie points were used to compare the accuracy of AAT to the triangulation performed with points coming from the analytical plotter. The photogrammetric block was fully constrained by assigning to all exterior orientation parameters of each image the values computed from the analytical procedure, weighted with the accuracy derived from l.s. bundle adjustment.

In this way the object coordinates of all the tie points were computed and then compared to those coming from the adjustment computed at stage 1 on TRIADIGIT measurements. The RMSs of the differencies between two coordinate sets is zero for the horizontal coordinates, while there is a significant bias for heights (251 cm). The behaviour of the st.dev of the differencies is opposite: they appear higher in *X* and *Y* directions (140 cm) than in *Z* (57 cm).

The three-dimensional distribution of these discrepancies clearly shows a systematic trend, particularly evident on the planimetric coordinates (see Fig. 7). The bias is probably due to the difference between analytical and digital interior orientation as well as to border effects at the strip ends, since the exterior orientation, as determined by the analytical plotter measurements, refers to the whole block of 24 images, while that computed by the measurements by TRIADIGIT only to 10 images . We could not know which corrections were apported to image coordinates measured on the analytical plotter and thus we applied an empirical model in order to try to correct them. Table 5 shows the results of the block adjustment with the RMS errors on check points in both cases: the application of the corrections gives some improvement but cannot completely remove the discrepancies. Since CALGE does not include additional parameters for self-calibration, we could not try a more appropriate correction model to compare the two data sets.

4. CONCLUSIONS

As already mentioned, the program is still under development and, in the light of the undergoing tests, may be revised to some extent. We are going to implement a better procedure to redifine the points within each level of the image pyramid; most important is also the implementation of visualization tools for interactive control point and tie point measurement and, less critical but useful, a better user interface.

A further improvement of the rejection procedure will come from the robust estimation of an Helmert transformation from the image coordinates of a pair of images, rather than just by the evaluation of the parallaxes, to improve the sensitivity of the test.

The test of the program on different block scales and with different terrain morphology may tell more on the interaction between the approximation of the exterior orientation and the number of identification errors.

Finally, the automation of the interior orientation will be soon operational.

Image pyramid level	*Pixel size (μm)*	*Image size (pixel)*	*# tie points found*	*# tie points rejected*	*# tie points rejected by mav*
4	448	511x511	11676	n.a.	n.a.
3	224	1022x1022	11351	325	195
2	112	2055x2055	10960	391	122
1	56	4110x4110	10209	751	77
0	28	8220x8220	6393	3816	1223

Table 4 - Tie points found by TRIADIGIT at every level of resolution

Stage	*# constraints*	*# control points*	*Ratio equation/ unknown*	*σ_0 [μm]*	*Measurement accuracy*			
					Tie points		*Check points*	
					RMS σ_{xy} (cm)	*RMS σ_z (cm)*	*RMS σ_{xy} (cm)]*	*RMS σ_z (cm)*
Outliers rejection	7	—	1.59	13.0	235	408	—	—
Minimum constraint	7	—	1.53	13.0	78	133	—	—
Check	60	2318	1.54	13.5	49	113	140	257
Use of the corrective model					—	—	*140*	51

Table 5 - Adjustment results of "Piemonte" block

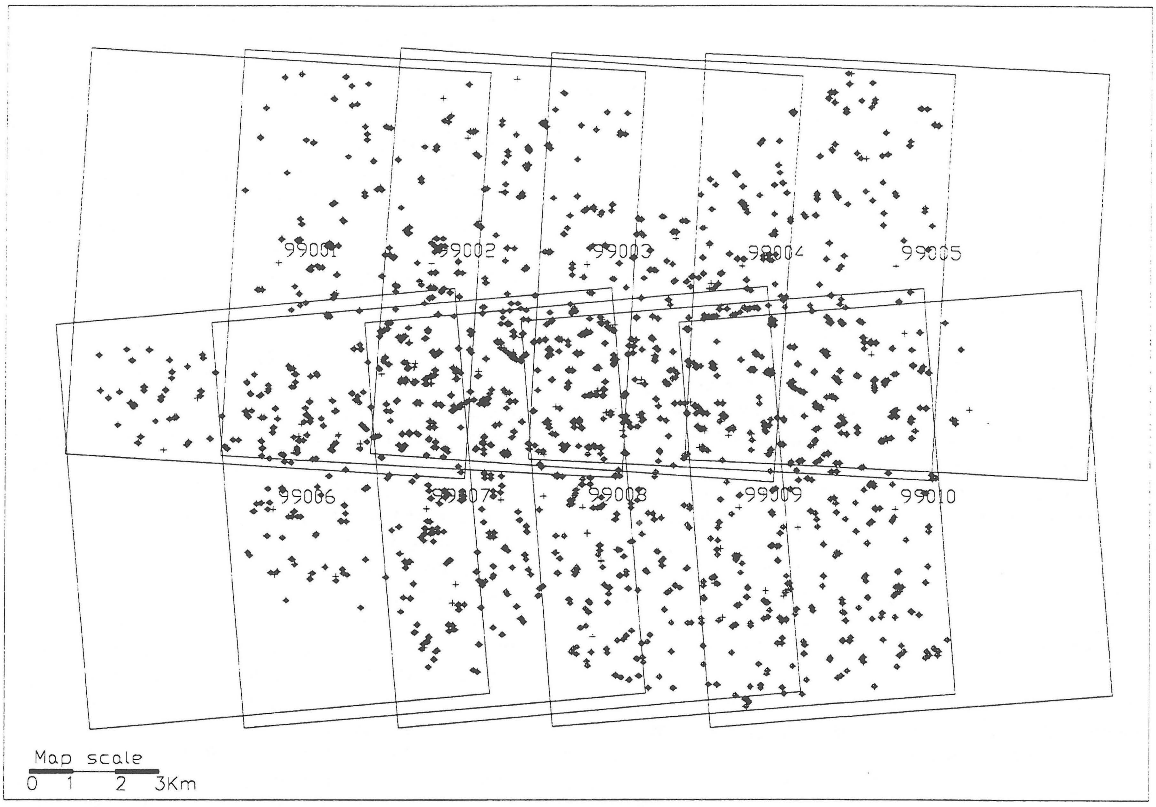

Figure 6 – Images of "Piemonte" block with all tie points determined by TRIADIGIT; points depicted without circle have been discarded after l.s. bundle adjustment

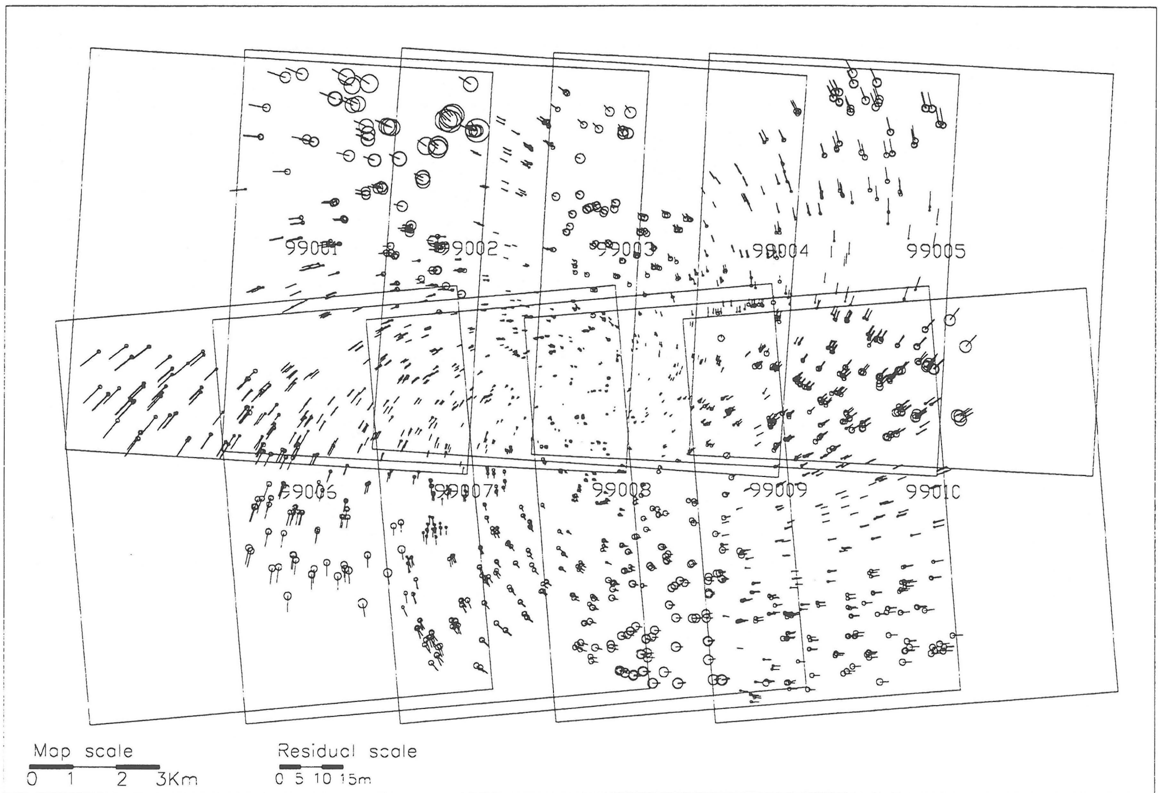

Figure 7 – Discrepancies between ground coordinates of tie points determined by adjustment with minimum constraint and by assigning to all the orientation parameters the value found on the analytical plotter (height residuals are represented by a little circle, after being subtracted of their mean value)

Acknowledgements

Compagnia Generale Ripreseaeree is gratefully acknowledgedfor providing the images of the test block and performing image scanning.
This work has been financially supported by funds COFIN-MURST (Prot. N. 9708224530).

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