Dense, reliable, and depth discontinuity preserving DEM computation from H.R.V. urban stereopairs

M. Cord†, N. Paparoditis‡*, and M.Jordan†
(†) ETIS / URA CNRS 2235, (‡) ESGT / CNAM, (*) LOEMI / IGN
e-mail: cord@ensea.fr, nicolas.paparoditis@ign.fr, jordan@ensea.fr

ISPRS Commision II, working group 6

KEY WORDS: DEM, H.R.V. aerial images, urban scenes, stereo processing, contour adaptive template shape matching, multi-resolution approach

ABSTRACT

In this paper, we develop a simple Digital Elevation Models processing scheme that focuses on the improvement of urban high resolution DEM basic properties such as density, reliability, accuracy, capacity to render 3-D landscape shapes and breaks to improve 3D-building models production but also urban orthophoto production.

Our basic single scale matching algorithm is based on a cross-correlation template matching to provide the denser depth maps as possible. In this algorithm, template windows are not rectangular, they are landscape adaptive. Contour grey-level image features are used to define the matching window shape thus preserving clean, sharp and well located depth and slope discontinuities. A sub-pixel disparity estimation is also used to enhance the matching accuracy and thus provides a smoother 3-D scene surface. An internal validation of the disparity measurements based on the study of symmetrical correlation coherence enhances the reliability of the process but therefore leads to sparser maps.

To obtain denser maps and to accelerate the matching process especially on very high resolution images where the disparity search intervals for the points to be matched can be very wide an thus lead to a combinatorial explosion, our single scale matching process is integrated in a multi-resolution matching strategy.

We show that our processing scheme stands very good results on a set of complex and various urban scenes images of different resolutions and different sensors.

RÉSUMÉ

Dans cet article, nous développons un processus simple de restitution de Modèle Numérique d'Elévation focalisé sur l'amélioration des propriétés des MNE haute résolution en zone urbaine à savoir densité, fiabilité, précision et aptitude à restituer les formes et les ruptures tridimensionnelles du paysage nécessaires et essentielles pour la production de modèles 3-D de bâti urbains mais aussi pour la production d'orthophotos urbaines.

Notre algorithme de mise en correspondance est basé sur la corrélation de vignettes photométriques pour produire les cartes d'altitudes les plus denses possibles. Dans cet algorithme, les vignettes de corrélation ne sont pas rectangulaires et de taille fixe; elles s'adaptent au paysage. Sur l'hypothèse que les ruptures de pentes ou d'altitude de la scène se caractérisent dans les images par des transitions radiométriques, les contours des images sont utilisés pour contraindre la forme des vignettes de manière à ce qu'elles n'englobent pas les transitions du relief dont les formes sont alors bien localisées et restituées. L'interpolation sub-pixellaire des disparités améliore la précision intrinsèque de la mise en correspondance et permet d'obtenir des cartes d'altitudes bien plus lisses. Enfin, une validation interne des disparités par étude de la cohérence des corrélations symétriques augmente la fiabilité du processus mais par contre altère la densité.

Afin d'obtenir des cartes plus denses mais aussi d'accélérer le processus de mise en correspondance d'images et surtout des images très haute résolution pour lesquelles les intervalles de recherches admissibles pour les points à apparier peuvent être très étendus et conduire à une explosion combinatoire, notre processus de mise en correspondance est intégré dans une stratégie multi-résolution spécialement adaptée aux caractéristiques des scènes traitées.

Nous montrons que notre processus global donne de très bons résultats sur un ensemble d'images urbaines complexes et variées de différentes résolutions et de différents capteurs.

1. INTRODUCTION

Urban scenes Digital Elevation Models are a key data to many applications such as urban orthophoto production, antenna's landscape visibility calculation for mobile phones telecommunications or to higher level date processing such as high scale mapping or 3-D city modelling. Requested properties for DEMs do of course depend on applications but are most of the time spatial density, depth and spatial accuracy, and reliability. Means of DEM production are meanly of two different natures: laser ranging-based and photogrammetry-based systems and techniques.

Laser ranging-based systems provide accurate but above all reliable depth maps [Haala 94]. Against that, system acquisition constraints limits the spatial density of the depth samples and therefore introduces a fuzz in depth discontinuities localisation.

Depth discontinuities localisation and 3-D shapes and slopes rendering are a key point for building detection, recognition [Baillard&Dissard 97] and reconstruction [Paparoditis&al 98] [Jordan&Cord&Cocquerez 98]. Furthermore, a very fine spatial density (beneath 20 centimetres) is unavoidable or for small or complex buildings made of aggregated planar section of roof. The 3-D statistical identification and estimation of each planar section of roof can only be carried out with a fairly large number of 3-D samples.(at least 100).

We believe that only **photogrammetry-based** techniques with very high scale photos or very high resolution digital images can stand such densities. Furthermore, only stereo photogrammetry can allow a real duality and combination of monocular and binocular analyses. However, DEM stereo computation from mid to high resolution aerial or satellite urban images is a very difficult task because of all 3-D structures, depth discontinuities, occlusion boundaries, slope breaks, and homogeneous, non lambertian and specular surfaces appearing at these resolutions.

Very few works have been committed to very high resolution images[Henricsson 96]. Among all the problems related to H.R.V. images an other major one appears for very H.R.V. images. Indeed, the extent of disparity variation can be so important that defining shifting areas for homologous points research, with an a priori knowledge of scene's relief extent, leads to a combinatorial explosion and to a rise of matching ambiguities which affects the reliability of the process.

2. IMAGE MATCHING APPROACH FOR SCENES WITH DEPTH AND SLOPE BREAKS

Numerous stereo matching algorithms dedicated to DEM computation have been developed in the last 25 years. They are usually sorted out into two classes.

Feature-based techniques aim at matching a smaller set of image points: image features often contours, segments, regions which are supposed to be characteristic structures of the scene. These techniques are thus fast but provide very sparse depth maps that are very difficult to interpolate with an *a posteriori* process. Furthermore, same image features do not always appear in both images especially when they correspond to depth discontinuities.

Template-based or area-based techniques measure the similarity of grey-level image templates around the points to be matched. It can be carried out on all image pixels and thus provides dense disparity maps. Templates are most of the time square and of fixed size throughout the image. Several template similarity measurement functions have been used in existing systems and all having interesting properties. the normalised cross-correlation functions allows the matching of templates with a global radiometric difference due to global luminosity changes between two views or due to slope effects on measured radiometry. Gradient correlation is also very interesting for template matching. It avoids problems that would encounter a grey-level cross-correlation for the matching of a window overlapping two joint and separate surfaces with different non lambertian behaviour. Furthermore, it is less sensitive to noise and the peak of the correlation curve stands out better [Crouzil&Massip-Pailhes&Castan 96].

Anyway, whatever the similarity function classical template matching is not capable of rendering well located, clean and sharp depth discontinuities. Indeed, the disparity associated with a pixel is a "mean" of all disparities in the template. Thus discontinuities are smoothed or delocalized (see Figure 2-1). To reduce these effects, template sizes can be reduced. In turn, the reduction of the texture sample leads to a rise in the correlation noise and in the number of mismatches. Template matching limits are due to the rigidity of the rectangular template pattern and of its fixed size. Template sizes and shapes should change according to the landscapes changes.

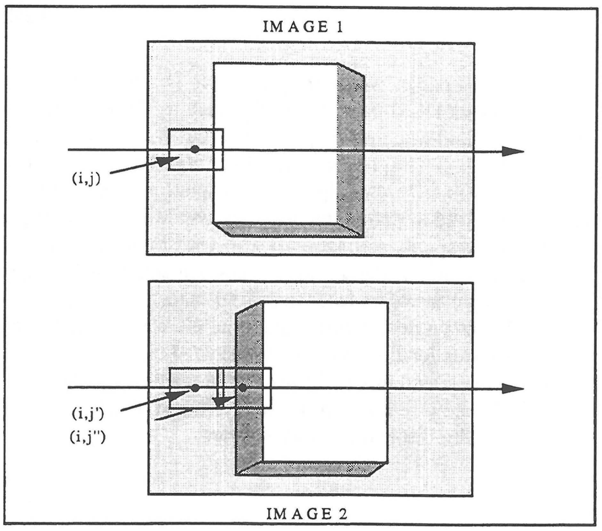

Figure 2-1: The real match (i,j) of image 1 should be (i,j'). Classical cross-correlation matching gives (i,j'') as best match for (i,j).

A few experiences of adaptive templates have been carried out. For guidance, template sizes can be fixed according to the local distribution of the grey-level image or/and of a coarse disparity map [Kanade&Okotumi 94] or to a largest rectangular size non overlapping a contour [Lotti&Giraudon 94]. This last technique provides the most efficient results in terms of density and depth discontinuity preservation but against that it is complex therefore time consuming and it is not efficient in areas between close contours.

2.1 A new landscape adaptive template matching technique

Our depth discontinuity preserving template matching is a very simple contour adaptive window shaping technique. It is based on the hypothesis that depth discontinuities and slope breaks are, most of the time, characterised by radiometric transitions in image space which can be described by a contour map obtained with any good edge detector. The idea is to prevent the smoothing disparity effects due to the use of pixels on the other side of a contour which could possibly have very different disparities. We thus change our classical rectangular template window against an adaptive shape template window including all inter-contour area (see Figure 2-2). This area contains all pixels on the same side of a contour and connected to the pixel (i,j) to be matched.

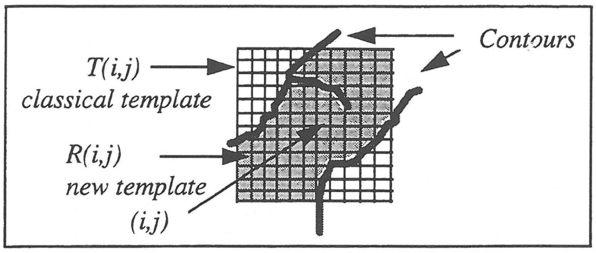

Figure 2-2: Contour adaptive window shape S(i,j) made from classical rectangular template window T(i,j). This pattern is built in the slave image.

Our adaptive windows similarity measurement (correlation score) between pixel (i,j) of image 1 (slave image) and pixel (i',j') is based on the normalised cross-correlation score and can be expressed:

$$C(i,j,i',j') = A \cdot \sum_{k=i-n}^{i+n} \sum_{l=j-m}^{j+m} S(i-k,j-l) \cdot \frac{I_1(i-k,j-l) \cdot I_2(i'-k,j'-l) - \mu'_1(i,j) \cdot \mu'_2(i',j')}{\sigma'_1(i,j) \cdot \sigma'_2(i',j')}$$

with

$$A = \frac{1}{\sum_{k=i-n}^{i+n} \sum_{l=j-m}^{j+m} S(i-k,j-l)} \qquad S(i-k,j-l) = \begin{cases} 0 \ si (i-k,j-l) \notin R(i,j) \\ 1 si (i-k,j-l) \in R(i,j) \end{cases}$$

and

$$\mu'(i,j) = A \cdot \sum_{k=i-n}^{i+n} \sum_{l=j-m}^{j+m} S(i-k,j-l) \cdot I(i-k,j-l)$$

$$\sigma'(i,j) = \sqrt{A \cdot \sum_{k=i-n}^{i+n} \sum_{l=j-m}^{j+m} S(i-k,j-l) \cdot (I(i-k,j-l)^2 - \mu'_1(i,j)^2)}$$

Our contour adaptive window matching technique is thus halfway between an area-based and a feature-based matching technique. This technique is as fast (or as slow) as the classical template correlation and its implementation is very easy.

This adaptive window shaping technique is not in competition with adaptive window sizing techniques. They are complementary. Adaptive window sizes are very helpful for homogeneous areas matching and adaptive window shapes are very helpful to preserve depth and slope discontinuities.

2.2 Building correlation surfaces

Previously to the template matching process, images are registered in epipolar geometry so that corresponding templates can be found by a simple shift along image lines. The minimal and maximal line shifts can be computed knowing the extreme altitudes of the scene. A correlation curve is usually built with all the correlation scores for all possible pixellar shifts along the line. We prefer building a correlation surface because we also allow shifts of one pixel along image rows. Indeed, we take into account possible row residues of the image registration process.

2.3 Sub-pixel disparity measurements

The estimated disparity is in this process and most of the time chosen to be the one that provides the highest peak in the correlation surface except for global matching techniques as least squares matching or dynamic programming matching [Baillard&Dissard 97] where lower scoring peaks can be chosen.

To improve the disparity measurement to a sub-pixel accuracy, a local bi-cubic interpolation of the correlation surface around the highest peak -using the 3x3 nearest neighbours- is carried out. The 3-D shapes in DEMs computed with sub-pixel disparities are much closer to real surface shapes (see Figure 2-3) thus easing 3-D cues extraction such as multi-slope roof line crests, roof planar section and others needed for building model .

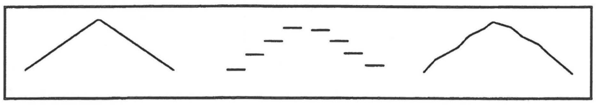

Figure 2-3: (Left) real roof shape, (Middle) roof shape with pixel disparity estimation, (Right) roof shape with sub-pixel disparity estimation.

2.4 Symmetric disparity internal validation

Pixels located in occluded areas, in periodic image patterns, or in homogeneous areas are frequently mismatched. A Matches are often rejected on the weakness of the correlation peak. A weak correlation score does not inevitably mean that the matching is not good. Indeed, correlation rates depend on texture and image quality. To avoid mismatches, we use a symmetrical disparity filtering procedure [Jones 91][Fua 92]. It studies the coherence between the disparity map computed with the image 1 as slave image and the disparity map computed with image 2 as slave image. We have adapted this internal validation technique to sub-pixel disparities estimations which strengthen the filtering efficiency and enhanced its robustness. The disparity value for a pixel (i,j) of image 1 is discarded if:

$$\underset{n\in 0..1, m\in 0..1}{Inf} \left\| \vec{V}(i,j) - \vec{V}'(\lfloor i+V_i(i,j)+n \rfloor, \lfloor j+V_j(i,j)+m \rfloor) \right\| \leq \tau$$

where $\vec{V}$ (resp. $\vec{V}'$) is the disparity of the image 1 (resp. 2), V_i (resp. V_j) is the line (resp. row) disparity component for a pixel of image 1 and τ is the tolerance on the internal coherence between symmetrical matching.

A quality assessment of this approach applied to on one meter realistic simulated satellite stereo-pairs has already been carried out [Paparoditis 98][Paparoditis&al 98] showing that the RMS disparity error is 0.25 pixels on flat surfaces like building roof tops and 0.28 for terrain relief. The evaluation shows that a major part of these errors are due to a bias that appears for every disparity estimation and whose importance depends on the fractional part of the real disparity.

3. MULTI-RESOLUTION MATCHING STRATEGY FOR VERY H.R.V. URBAN IMAGES

3.1 Multi-resolution strategy

Working on decimetre resolution images has an impact on the choice of a specific matching strategy. Very high resolution images offer large and poorly textured surfaces. Therefore, the correlation scores are reduced and then, mismatch probability is raised. This fact is all the more so pronounced since initial search matching space is large.

Besides, occlusion areas are very large and variously spread out in the very high resolution images. Buildings, trees and big raised structures generate very large occlusion areas which increase wrong matches. Many other small structures as low walls, parapets, chimneys, cars, etc., generate small occlusion areas. They are spread only on few pixels but their radiometric contents can seriously disturb the correlation scores.

Moreover, in decimetre resolution images, the local disparity variation can be very important compared to metric resolution images, thus leading to a combinatorial explosion. To overcome these computational and image matching problems, a multi-resolution matching strategy is proposed. In fact, we believe that, for a given resolution scale and a given template size, the matching is variously successful in accordance with the considered scene objects. Some roofs offer a rich texture at the full resolution scale which drives matching dense and reliable. Other roofs, on the other hand, are homogeneous at the full resolution scale; then, the matching is poor and not reliable. However, after decimation, the size of the homogeneous areas is reduced and some structures as borders, chimneys, ledges, make the roof point matching successful at a shading off resolution scale. Thus, an optimal resolution scale for a given template size can be found for the best matching of each structure of the scene. Moreover, the radiometric disturbance problems due to occlusions are reduced at coarser scales, thanks to the smoothing effect of the decimation process.

Our multi-resolution matching process is based on a "coarse to fine" strategy. However, rejection and correspondent search path modification process is introduced. If a coarser resolution scale disparity value does not make a satisfactory matching at a finer resolution scale, it is removed and the matching process is carried out with the maximum initial disparity search space. The limitation of the classical cross-correlation (see section 1) have encouraged us to develop an adapted stereo approach where adaptive window matching is combined with multi-scale matching process.

3.2 Multi-resolution matching scheme implementation

To build the multi-scale pyramid, the initial image is smoothed and sub-sampled to obtain the reduced images [Burt 84]. We selected a filter for the image pyramid construction not only according to the quality measurement of the pyramid but also to that of the whole matching process. For each level of the pyramid we compute a contour map needed for the adaptive template matching process. The edge detector filter size is adapted to image scale.

At each level of the pyramid, the adaptive template matching strategy is applied with the corresponding contour map. The template window size is the same through the scale space.

The disparities calculated at a coarser level are filtered using the two way filtering technique and the non-rejected disparity values are extrapolated without any preview densification at a finer level. Then, they are used to initialise the finer level disparity search interval. For all rejected disparity pixels, the search interval is the maximal interval associated with the finer level. The whole matching scheme is carried out on the Figure 3-1.

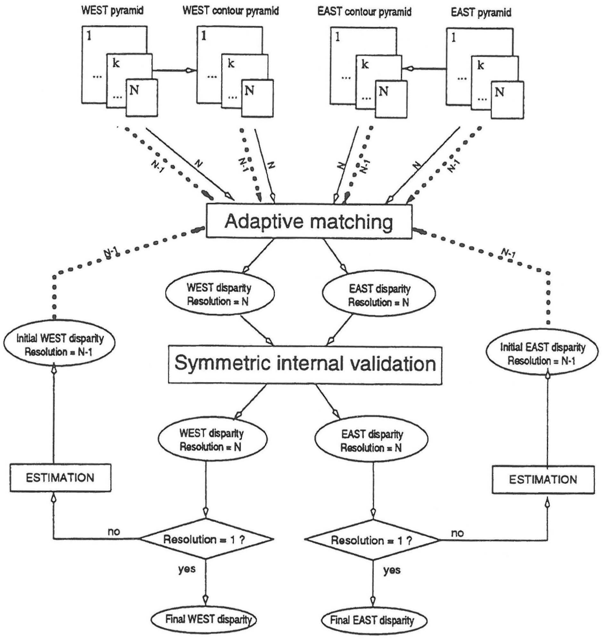

Figure 3-1: Multi-resolution matching scheme.

The depth of the pyramid is a determinant parameter of the multi-scale matching approach. This factor N is relied to the initial disparity ΔP_1 and to the final disparity ΔP_N by the relation:

$$N = \left\lfloor 1 + \frac{\log(\frac{\Delta P_1}{\Delta P_N})}{\log(2)} \right\rfloor$$

ΔP_1 may be fixed by an *a priori* knowledge of the scene relief and the system calibration. Moreover, the first search interval ΔP_N may be reasonably fixed around 20 pixels to provide a satisfactory first correlation surface. As a result, N is automatically computed from ΔP_1.

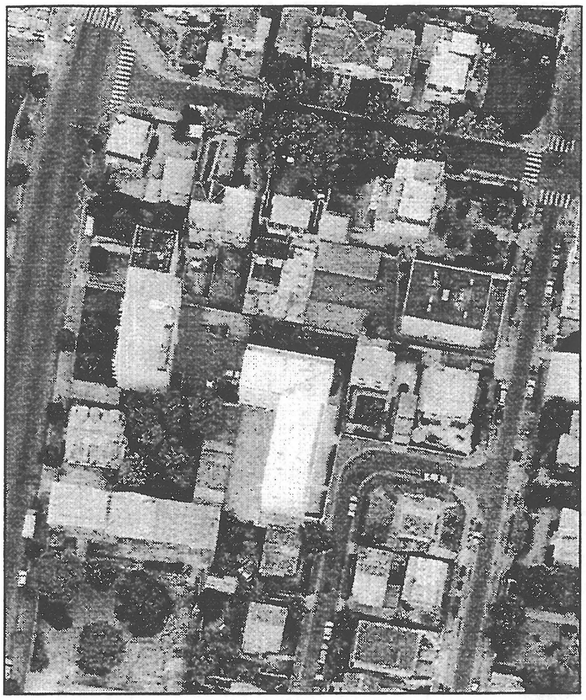

Figure 4-1 : 2000x2000 West sub-image

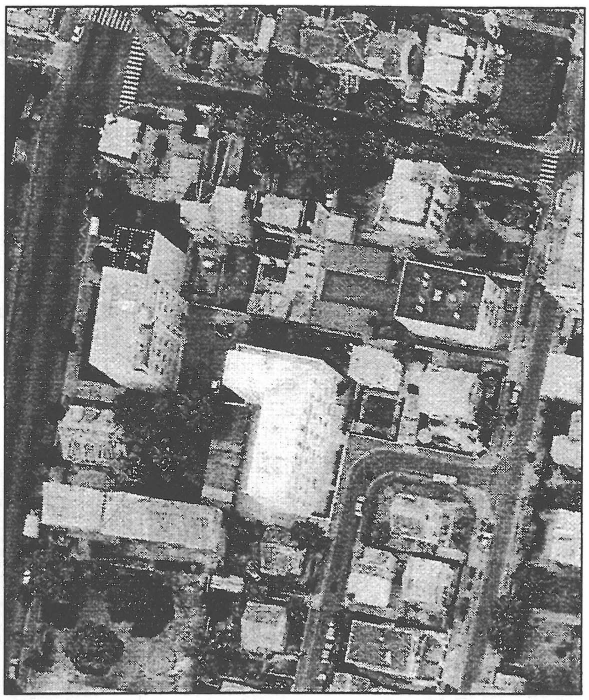

Figure 4-2 : 2000x2000 East sub-image

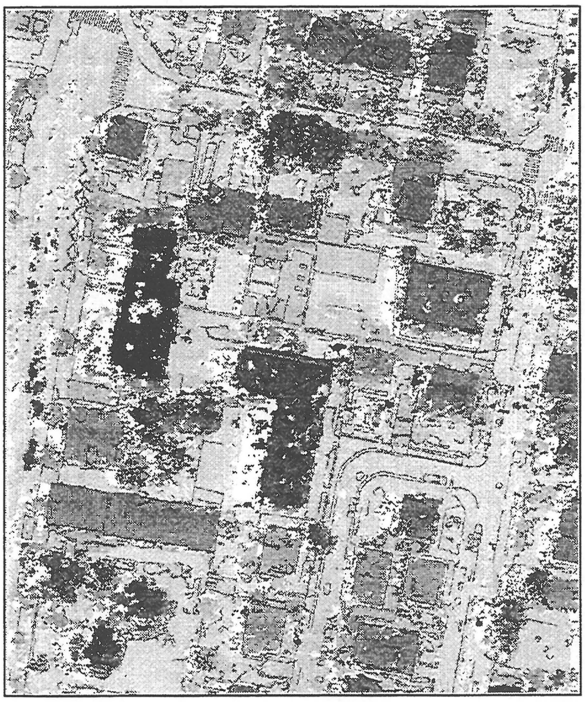

**Figure 4-3 : Contour adaptive multi-resolution matching.
Pyramid_depth = 3, beta_shen = 1.0,
Maximal template sizes = 15x15.
White areas correspond to unmatched pixels**

4. RESULTS

4.1 Application to 8 cm digitised aerial images

On the first result we present our stereo scheme on a 2000x2000 stero-pair of 8 centimetres resolution extracted from 6.000x 10.000 digitised aerial stereo-photographs supplied by the IGN and covering the French city of Colombes (see Figure 4-1 and Figure 4-2).

The disparity grid/map obtained with our stereo scheme is dense, reliable and accurate (see Figure 4-3). Disparities fill the image grid up to the contours. Depth discontinuities like roof tops boundaries are properly and sharply preserved and localised. Even the low elevation structures are well reconstructed.

Other results with and without adaptive template matching and with and without multi-resolution matching process are provided on two smaller images one containing flat and rectangular roof top buildings (see Figure 4-12) and the other containing sloped roof top buildings (see Figure 4-4). Results on both extracts clearly show that the multi-resolution strategy provides better results than the ones that are obtained with a single resolution scale matching. In fact, multi-resolution makes results more dense and reliable. This improvement is particularly visible on Figure 4-13 where homogeneous areas are large and spread out.

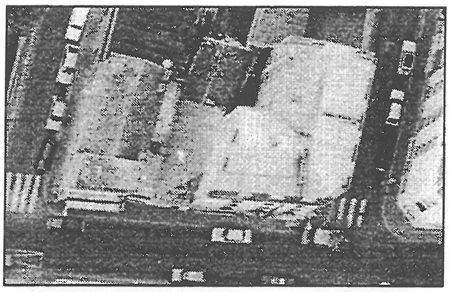

Figure 4-4 : slave image of multi-slope roofs

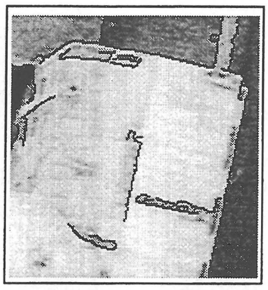

Figure 4-5 :Detail of Figure 4-4 with contour map printed in

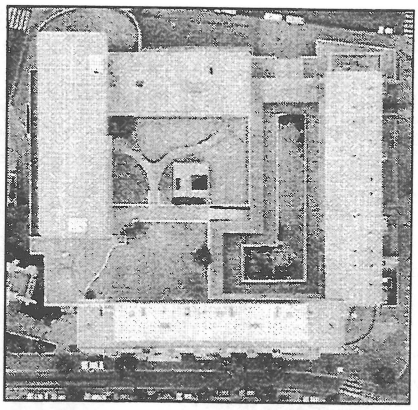

Figure 4-12 :Slave image of apartment houses

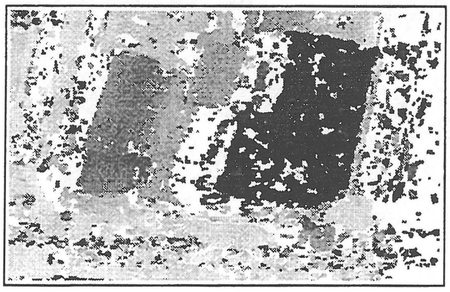

Figure 4-6 : Single-resolution matching

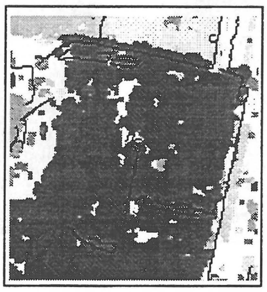

Figure 4-7 :Detail of Figure 4-6 with contour map printed in

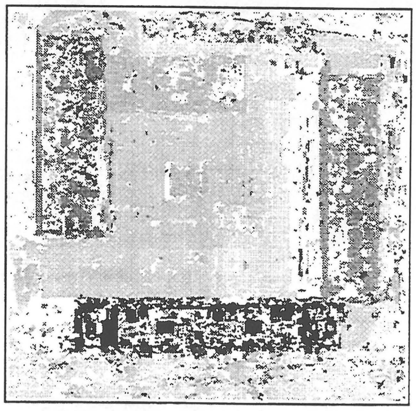

Figure 4-13 : Single-resolution disparity

Figure 4-8 : Multi-resolution matching

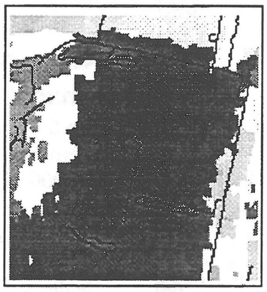

Figure 4-9 : Detail of Figure 4-8 with contour map printed in

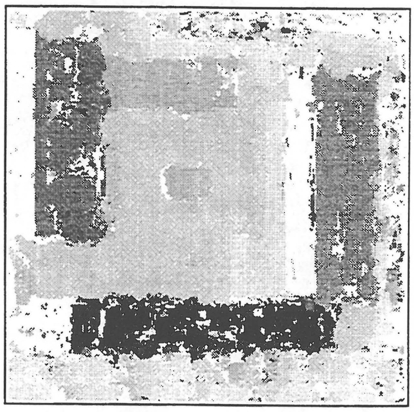

Figure 4-14 :Multi-resolution matching

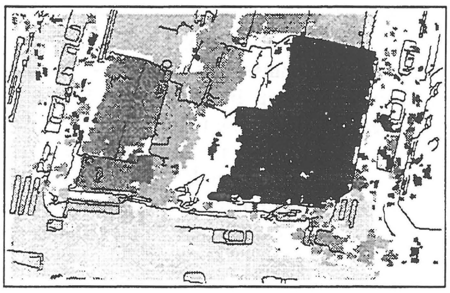

Figure 4-5 :Contour adaptive multi-resolution matching

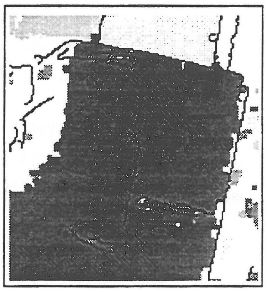

Figure 4-11 :Detail of Figure 4-10 with contour map printed in

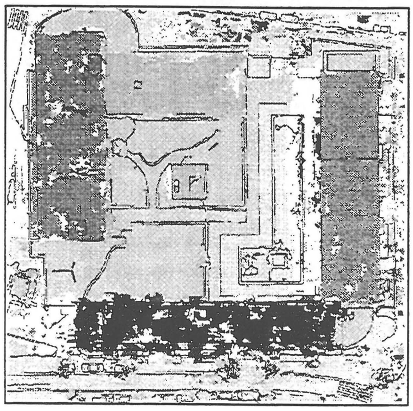

Figure 4-15 :Contour adaptive multi-resolution

However, multi-resolution scheme without adaptive template matching (see Figure 4-9) is not satisfactory; the depth discontinuities of the roof tops boundaries are not preserved and not properly localised. Multi-resolution matching with adaptive template shapes matching corrects this lack and then provides not only dense maps but also well preserved and localised roof tops boundaries and more generally depth discontinuities (see Figure 4-11).

It is important to note that disparity maps are in some places sparse because some areas are too homogeneous (template texture is noise) or saturated (template has no texture at all). This is due to the poor image quality of the stereo-pair.

4.2 Application to images of aerial digital frame camera

Figure 4-16 shows an 80 centimetre left image of a stereopair captured with the IGN aerial digital frame camera. This complex building is the "la Fourvière" railway station in the town of Lyon in France.

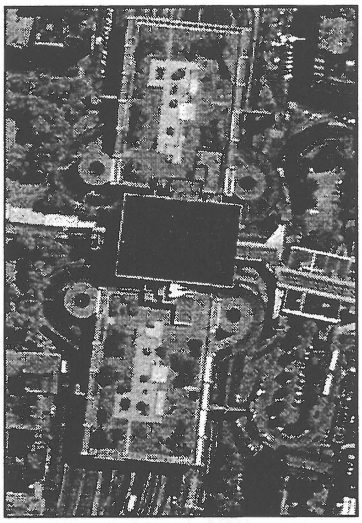

Figure 4-16 : Left image of Fourvières railway station stereopair

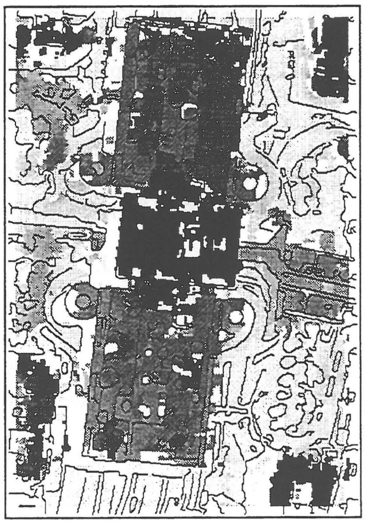

Figure 4-17 : Fourvières railway station disparity map in image space

The disparity map results (see Figure 4-17) on this digital stereo-pair confirms our belief that the key point to image matching is image quality. The dark and very homogenous roof top in the middle of the image has been matched in a dense and precise way. Thus, the better the quality, the easier the matching. For high quality images, smaller window sizes are sufficient and thus would allow the matching of slope roof sections that bigger windows could not allow.

4.3 Application to the famous Pentagon stereo-pair

We have processed a disparity map on the very well known and used Pentagon stereo-pair so that the reader can compare our results with existing results.

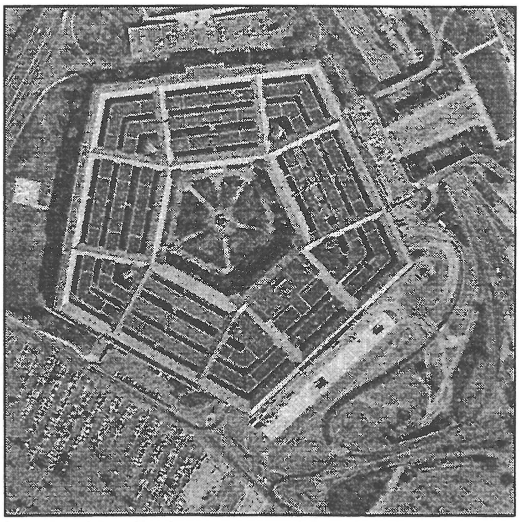

Figure 4-18: Left image of Pentagon stereo-pair

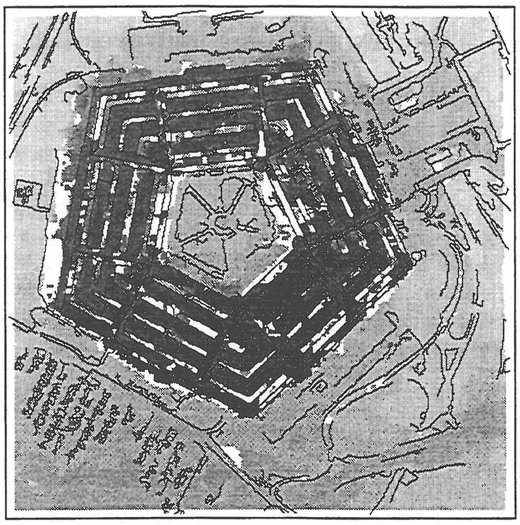

Figure 4-19 : Pentagon computed disparity map in image space

5. CONCLUSION AND PROSPECT

In this work we have described a complete DEM processing scheme adapted to H.R.V. and very H.R.V. aerial or satellite images combining monocular, binocular and multi-resolution analyses which improves surface reconstruction for landscapes with depth and slope discontinuities and stereo-pairs with very important disparity variations.

This stereo approach can be applied to other kind of outdoor landscapes and to other kinds of imaging systems, for instance robot images of Martian landscapes also presenting important depth and slope discontinuities.

Several fields of investigation can be pointed out. Some related to the use of new data and some others to the use of improved matching techniques.

5.1 System improvements

This scheme will soon be applied to the new 3000x2000 colour images of the IGN digital camera [Thom&Souchon 98]. These colour images should improve correlation rates, reduce matching ambiguities, improve DEM density in homogeneous regions, and globally enhance the robustness of contour detection for depth discontinuities preservation.

The IGN image acquisition policy for 3-D urban scenes mapping and building models reconstruction with the new 4096x4096 panchromatic aerial digital frame camera of IGN is to have a 80% recovery between two consecutive images in a same acquisition strip and 60% recovery on two successive strips. Thus, each ground point is seen at least in six different images. Adapting our image space matching approach to a matching approach guided from object space will allow more than two views image matching -with an adapted multi-dimensional correlation score- and should also improve matching reliability and density.

5.2 Template matching improvements

One of the most important limitations of templates matching carried out from image space is that no points on important slopes such as sloped roofs can be template matched because of different surface projection in both images. One could thus imagine that for all non matched pixels -and all non occluded areas which could be determined by a z-buffer technique on all matched samples- a new correlation process with new unknown quantities to estimate, i.e. slope parameters, in addition to classical shifts parameters, should improve slope matching by allowing slope-adaptive window shaping.

REFERENCES

[Burt 84] P.J. Burt, The Laplacian Pyramid as a Compact Image Code, IEEE Trans. on Communications, 1984, vol. 31, number 4, p 532-540.

[Baillard&Dissard 97] C. Baillard and O. Dissard and O. Jamet and H. Maitre, Extraction and characterization of above-ground areas in a peri-urban context, Proc. of the IAPR/TC-7 workshop on methods for extracting buildings, roads and other man-made structures from images, 1996, Graz.

[Cord&Huet&Philipp 97] M. Cord and F. Huet and S. Philipp, Optimal Adjusting of Edge Detectors to Extract Close Contours, SCIA, June 1997, Lappeenranta, Finland.

[Cord&Jordan&Cocquerez] M. Cord and M. Jordan and J.P. Cocquerez, Towards semi-automatic control of topographic data bases from aerial images, ISPRS Commission II Symposium, July 1998, Cambridge, England.

[Crouzil&Massip-Pailhes&Castan 96] A. Crouzil and L. Massip-Pailhes and S. Castan, Mise en correspondance par correlation des gradients, Reconnaissance des formes et intelligence artificielle, AFCET, Jan. 1996, Rennes, p 236-245.

[Fua 92] P. Fua, Combining Stereo and Monocular Information to Compute Dense Depth Maps that Preserve Depth Discontinuities, Int. Joint Conf. On Artificial Intelligence, 1991, p 1292-1298.

[Haala 94] N. Haala, Detection of buildings by fusion of range and image data, ISPRS, 1994, Munich.

[Henricsson&al 96] O. Henricsson, Inferring Homogeneous Regions by Combining Contour Relations and Rich Images Attributes, Institute for Communications Technology, Image Science Lab, 1995, ETH, Zurich, Switzerland, number BIWI-TR-162.

[Jones 91] D.G. Jones, Computational Models of Binocular Vision, 1991, Stanford University.

[Kanade&Okotumi 94] T. Kanade and M. Okutomi, A Stereo Matching Algorithm with an Adaptative Window: Theory and Experiment, I.E.E.E. Trans. on Pattern Analysis and Machine Intelligence, 1994, vol. 16, number 9, p 920-932.

[Lotti&Giraudon 94] J.-L. Lotti and G. Giraudon, Adaptative window algorithm for aerial image stereo, 12th Int. Conf. on Pattern Recognition, 1994, Jerusalem,p 701-703.

[Paparoditis 98] N. Paparoditis, Reconstruction 3D de scènes péri-urbaines à partir d'images satellites stereoscopiques haute resolution, 1998, Univ. de Nice, Sophia-Antipolis.

[Paparoditis&al 98] N. Paparoditis and M. Cord and M. Jordan and J.-P. Cocquerez, Building Detection and Restitution from High Resolution Aerial Imagery, Computer Vision and Image Understanding, 1998, Accepted for publication.

[Thom&Souchon 98] C.Thom and J.P. Souchon, Le point sur les images de la caméra numérique de l'IGN, Bulletin S.F.P.T, Mars 1998.

[Witkin 87] A. Witkin and D. Terzopoulos and M. Kass, Signal Matching Through Scale Space, International Journal of Computer Vision,1987, p 133-144.