RELIABILITY AND ACCUARCY OF AUTOMATICALLY GENERATED DEMs FROM SPOT IMAGES

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KEY WORDS: SPOT, automatic DEM generation, accuracy analysis

ABSTRACT

The research described in this paper is aimed at examining the possibility of using SPOT images for automatic generation of digital elevation models (DEMs). The research study discusses several aspects of the subject: accuracy of the geometrical solution with different ground-control-point configuration; accuracy of the results obtained by the automatic procedure with different algorithms and different land cover characteristics; and reliability of the results.

The study is based on using existing technology for the geometric solution of the model and for DEM generation. The results of the automatic procedure are compared to the results of interactive measurements of DEMs from aerial photographs in the same areas. In general, it can be observed that the accuracy of DEM derived automatically from SPOT images is better than 10 *m* for most cases. However, there is still a reliability problem in certain areas. The characteristics of these areas can be pointed out. Future research on this subject should concentrate on automatic quality control of DEM results. Such a quality control, although not expected to solve all the problems, will improve the reliability of the results considerably, even in difficult areas.

1. INTRODUCTION

A *Digital Elevation Model* (DEM) is a model that describes the ground surface accurately and reliably. A DEM constitutes part of the infrastructure of every modern country. Its importance is increased with the tremendous progress in the fields of GIS, digital photogrammetry and remote sensing. Besides conventional applications like generating contour lines or profiles, a DEM is also used nowadays for generating new digital products. Among these products are digital orthoimages, perspective views and "fly through" sequences. These products, especially digital orthoimages, are accepted today as standard mapping tools.

Traditionally, a DEM is generated from a stereoscopic model of partially overlapping aerial images. In recent years, SPOT images are also used for DEM generation. SPOT is the first satellite that enables stereoscopic coverage. Using satellite images instead of aerial images has the advantage of having a large area covered by one model, without the need to combine pieces of information that are measured on different models. A DEM obtained from such a single model is more consistent, provided that the geometric solution is sufficiently accurate. The main disadvantage is the resolution, which is relatively low (10 *m*). However, such resolution is sufficient for a large number of applications.

Using digital imagery in general, and SPOT images in particular, provides the opportunity for automating the DEM generation process, by using image-matching techniques. In the past two decades, digital image matching has been the subject of numerous research studies by the photogrammetric and computer vision communities (for extensive reviews see, e.g., Baltsavias, 1991; Doorn *et al.*, 1990; Hannah, 1988; Wrobel, 1988). Recently, these extensive research studies have started to show fruits as commercial software packages.

The research described in this paper is aimed at examining the possibility of using SPOT images for automatic DEM generation. The following aspects are addressed:

- Accuracy of the geometric solution of the stereo model;
- Reliability of the results obtained by an automatic procedure;
- Accuracy of the results obtained by an automatic procedure.

The study is based on existing technology for geometric solution of the model and for DEM generation. The results of the automatic procedure are compared to the results of interactive measurements of DEMs from aerial photographs in predefined areas. These interactive measurements are more accurate, due to the larger scale of the photographs, and therefore can be considered as "ground truth." The number of points compared is large, in order to perform a proper statistical analysis and to cover a variety of problems that may pertain in the data. This approach is different from what was done in the past (see Bolstad and Stowe, 1994; Chen and Lee, 1993; Sasowsky and Paterson, 1992; and Zilberstein, 1995), where a relatively small number of points were tested.

The paper discusses the following subjects:

- The SPOT images that were used for the tests, and the ground control points for solving the geometry of the stereo model;
- The solution of the model and its accuracy;
- The test areas and their characteristics;
- The comparison between the DEM obtained automatically, and the reference data measured interactively.

2. SPOT IMAGES AND CONTROL POINTS

2.1. Selection of the SPOT model

The DEM is generated from a pair of panchromatic SPOT images, with a resolution of 10 *m*. An optimal geometric solution (in terms of accuracy) is obtained when two images that cover the same scene are taken from paths that are as far apart as possible. The disadvantage of the obliquity is minor compared to the accuracy advantage.

A primary consideration in selecting the model for this research study was the requirement for including a variety of land cover characteristics. In addition, the accessibility of the areas of the model was also considered, in order to enable ground measurement of control points.

The selected images contain SPOT scene number 119-287. The scene covers populated areas (the towns of Beer-Sheva, Ashkelon, Gaza and more), agricultural areas in the western part of the Negev district, mountainous areas at the southern Hebron Mountains and desert sandy areas east of the town of Beer-Sheva. Most parts of the scene can be physically accessed, so obtaining control points did not present any major problem.

2.2. Selection of control points

In order to solve the stereo model with high accuracy, ground control points are required. The number of points needed is depended on the mathematical model. Usually, a relatively small number of points are required (less than 10). These points should be homogeneously distributed over the model. In this project, 25 ground control points were measured in the field by differential GPS. The large number of points enables a careful analysis of the geometric solution, using different point configurations, while points that are not used for the solution serve as check points.

Selection of appropriate ground control points is a non trivial task. Points should be clearly visible and measurable on the images. The selection of points was therefore based on four steps:

1. A careful examination of the images and selection of potential measurable points, like buildings or bright surfaces, traffic islands, road intersections or clear curves on roads.
2. A preliminary (one day) tour for identifying the points in the field. Some candidate points were eliminated and others have been added.
3. GPS measurements of the points (three days). Connections to the national horizontal and vertical frames were done.
4. An adjustment of the GPS network and calculation of the ground coordinates both in WGS84 and in the Israeli horizontal and vertical coordinate frames.

Figure 1 depicts different types of control points that were selected and measured. During the examination of the results it was found out that despite that the measurement of points on bright surfaces over dark background seemed trivial, these points showed the largest errors. A possible explanation for that is the fact that the actual size of these bright areas on the ground is smaller than what appears on the images. The other types of points presented approximately the same, better, accuracy.

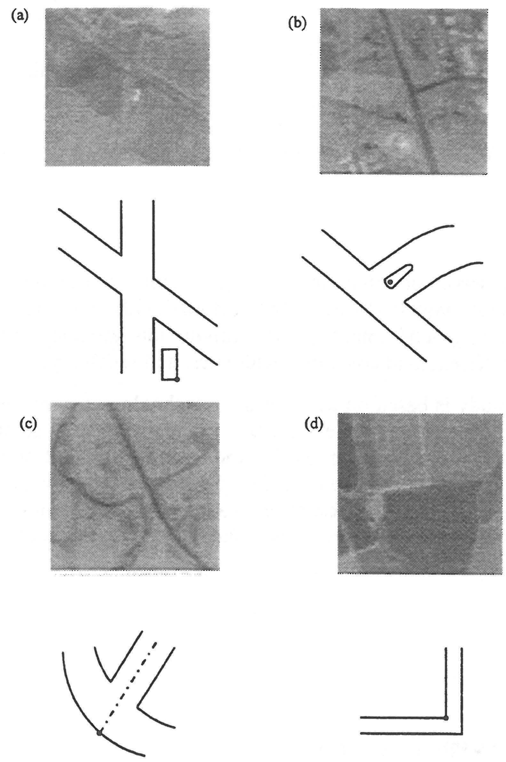

Figure 1: Different types of ground control points

3. GEOMETRIC SOLUTION OF THE MODEL

Mathematical models for solving the geometry of SPOT stereo model were developed in the past ten years (see, e.g., Kratky, 1989; Westin, 1991; Orun and Natarajan, 1994). In this research, three software packages were used independently for solving the geometrical model:

- TRMST (from TRIFID), under the Intergraph photogrammetric environment. This working environment enables a resampling of the images to epipolar geometry according to the geometric solution. Further stereoscopic work is performed in a way similar to aerial images. With this software, several ground-control-point configurations were tested.
- ORTHOMAX, under the Erdas-Imagine environment. This package contains also automatic DEM generation module. With this software, only one configuration (including all good control points) was tested.
- Software for solution of SPOT models under the environment of GeoImage, France. This solution was obtained by the company, and no details were provided.

An indication for the accuracy of the solution, when using all possible points, is obtained from the residuals of the adjustment procedure. For the TRMST solution, the maximum residual was approximately 1.25 pixels, while most residuals were smaller than 0.5 pixels. These results are acceptable, concerning the difficulties in accurate identification of the ground point on the image. With the ORTHOMAX package, residuals which are somewhat larger were observed. The maximum value was 2.5 pixels, while most other residuals were smaller than 1 pixel. The reason for the different results is probably the measuring process, and not the mathematical model, which is similar for both packages.

Using a smaller number of points for the adjustment and using the others as check points showed that it is possible to obtain an acceptable solution when there are points on the eastern and western parts of the scene. These results are in accordance with Zalmanson's findings (Zalmanson, 1994). A detailed description of the different configurations that were tested is left for another paper.

4. REFERENCE DATA

In order to investigate the accuracy and reliability of the elevations obtained by the automatic procedures, test areas were defined. These areas were selected according to certain land cover characteristics, from which conclusions may be drawn concerning the reliability and accuracy of the current technologies for automatic DEM generation.

Four areas were selected (Figure 2):

- A desert area (DESERT): a dry hilly area east of the town of Beer Sheva.
- An agricultural area (WNEGEV): fields with low vegetation, and bare fields in the western part of the Negev district.
- A mountainous area (HEBRON): a mountainous surface patch east of the town of Hebron.
- An urban area (BS): parts of the town of Beer Sheva. This area is characterized by man-made objects.

For each of these areas, a DEM was measured interactively, using aerial images with a scale of 1:40,000, on an Intergraph photogrammetric station. Details about these reference data sets are shown in Table 1.

Table 1: Manually measured reference elevation points

	number of models	scanner	resol. μm	measured points
DESERT	2	PS1	14	13,159
WNEGEV	2	RM-1	12	29,747
HEBRON	3	RM-1	12	20,934
BS	2	PS1	14	7,285

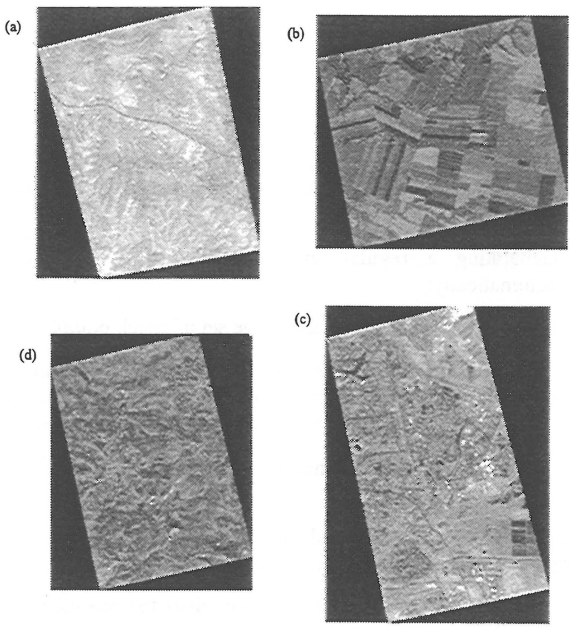

Figure 2: Content of the test areas:
(a) DESERT; (b) WNEGEV; (c) BS; (d) HEBRON.

5. COMPARISON BETWEEN AUTOMATICALLY DERIVED DEM AND REFERENCE DATA

5.1. Automatic generation of DEM

Automatic generation of DEM was performed in this research by three software packages:

- MATCHT (from Inpho, Germany), under the Intergraph photogrammetric environment. This package performs hierarchical matching of interest points.
- ORTHOMAX package, under the Erdas Imagine environment. This package performs hierarchical matching, based on cross-correlation of rectified images. The rectification is based on the available DEM at each stage of the process.
- GEOTOPO package (from GeoImage, France). No details are available.

A DEM was produced for each of the test areas, with an interval of 50 *m*. The overlap between the areas that were measured interactively and the areas for which DEM was extracted automatically was not complete. Nevertheless, each of the tests included thousands of points, so careful examination of the behavior of the software was possible.

5.2. The comparison

The comparison between the DEM obtained automatically and the manually measured points was performed in the following way:

- Generating a regular grid out of the DEM obtained automatically;
- Loading the manual DEM as a large set of check points;
- For each check point, using the horizontal position for extracting the elevation from the grid (by interpolation), and comparing this elevation to the elevation of the check point;
- Performing a statistical analysis of the results.

The quality of a DEM resulted from an automated procedure was examined with respect to two aspects:

- The reliability of the procedure, i.e., does the procedure actually measure a point on the ground, or the matching is wrong and the elevation value for this particular point can be considered as a blunder.
- Among all the points that are not blunders, how accurate is the DEM. In other word, how good is the mathematical model of the matching, and does it provide the optimal point.

Table 2 presents the results for the three software packages, and for all the test areas. For each test area, the first line shows the total number of points compared, the second line presents the percentage of points for which the error is smaller than 25 *m* (threshold that was selected for defining a point as a blunder). This line is a good indication for the reliability of the results. The third line shows the elevation error that was calculated for the reliable points. An extensive, detailed description of the results can be found in Krupnik (1997). As for the GEOTOPO package, no DEM was provided for WNEGEV. In addition, the DEM that was provided for the HEBRON area had a systematic error that could not be extracted without using the software, that (as described earlier) was not available. Therefore, for this package, only two test areas were compared. It should be noted also that the comparison between the three packages is only a by-product of the study. Since the testing conditions were different for these packages, one should not consider this comparison as a recommendation to use one of them.

Analyzing Table 2, one should realize that the performances of the three packages are similar for the simpler areas (BS and DESERT). For WNEGEV and HEBRON, the results are inferior. The MATCHT package performed somewhat better than ORTHOMAX, especially in HEBRON. Surprisingly, the results for the urban area (BS) are the best for all the packages, despite the fact that the area contains buildings, some of which are relatively tall. The reason for that is the fact that the area contains a large number of features, that probably compensated for the elevation differences. These determinations hold both for the reliability and the accuracy questions.

Figure 3 and Figure 4 show images of the differences between the measured points and the DEM generation results, for all test areas, for the MATCHT and the ORTHOMAX packages, respectively. In these figures, black areas indicate that no reference data is available, and white areas indicate errors of more than 35 *m*. Other gray values indicate different error levels, where the brighter the color, the higher the error.

Examining Figure 3 and Figure 4, shows that it is possible to characterized the areas that present large elevation differences into two categories: small areas, that are caused by a local failure of the process, and large areas, that point to a significant problem. Regarding the first category, a relatively simple filtering operation of the resulted DEM can solve most of the problems. The second type of problems is observed along the road on the DESERT data set (in particular, for the MATCHT package), along deep creeks on the HEBRON data set (in particular, for the ORTHOMAX package) and in the presence of agricultural areas with homogeneous gray values and repetitive patterns on the WNEGEV data set. A lengthy discussion on the subject can be found in Krupnik (1997).

Table 2: Results of the comparisons

Area		MATCHT	ORTHOMAX	GEOTOPO
DESERT	# points	13,091	13,030	13,159
	% above 25 m	96	99	100
	Accuracy (m)	8.3	7.7	7.4
WNEGEV	# points	26,270	25,595	
	% above 25 m	90	85	
	Accuracy (m)	9.7	11.1	
HEBRON	# points	28,776	28,567	
	% above 25 m	91	93	
	Accuracy (m)	7.7	9.7	
BS	# points	6,441	6,250	4,500
	% above 25 m	99	100	100
	Accuracy (m)	7.7	5.9	5.1

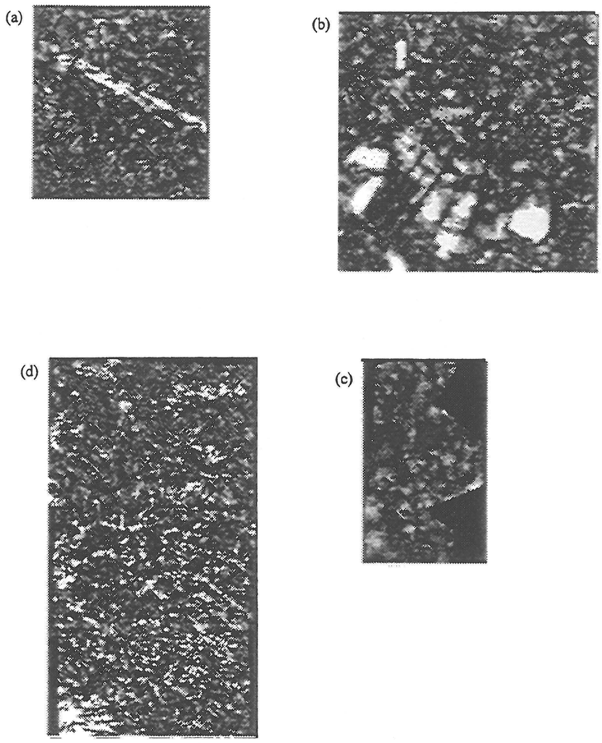

Figure 3: Differences for the MATCHT package: (a) DESERT; (b) WNEGEV; (c) BS; (d) HEBRON.

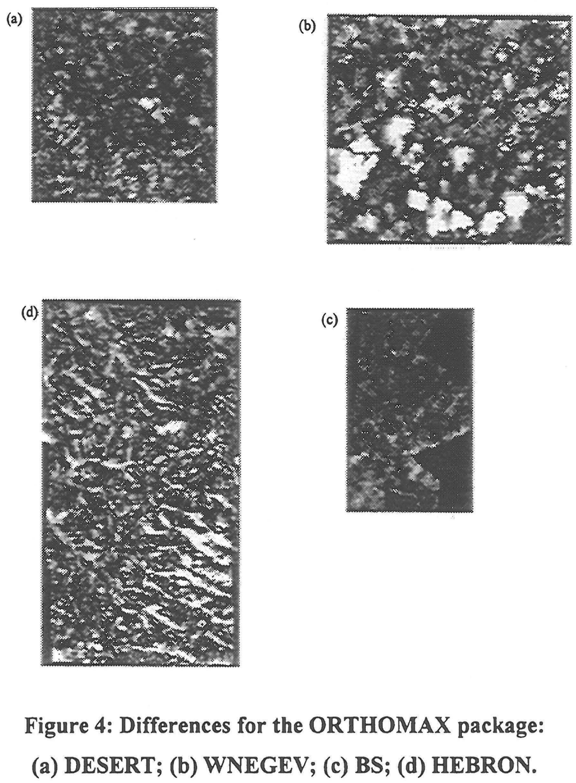

Figure 4: Differences for the ORTHOMAX package: (a) DESERT; (b) WNEGEV; (c) BS; (d) HEBRON.

6. SUMMARY AND CONCLUSIONS

The research described in this paper deals with the accuracy and reliability of DEM generated automatically from SPOT images. The accuracy and reliability were tested by comparing the DEM to a large number of points that were measured interactively. The comparison is performed for areas that represent certain land cover characteristics: a desert area, an agricultural area, a mountainous area and an urban area. The automatic DEM was generated by commercial software packages.

The results of the comparison show that there is a reliability problem of the DEM in agricultural areas. Tests with two different software packages, that are based on different technologies, show large areas for which the generated DEM is considerably different from the correct elevations. The results from the ORTHOMAX package also show problems in difficult mountainous areas which are characterized by deep creeks. The MATCHT software failed in reconstructing the surface around a desert road that runs nearly parallel to the epipolar lines. In addition, results from this package suffered more from local problems, as shown in Figure 3. These problems, however, can be treated by improving the low-pass filter that is convolved with the resulted DEM. Surprisingly, the results obtained for the urban area were extremely good for all three software packages.

Concerning the accuracy of the elevations (excluding blunders), one can realize that the results for all three packages are very promising. For all the areas, except for the agricultural area processed by the ORTHOMAX package, the accuracy is better than 10 *m*. For the urban area, the results are even better.

There is no doubt that future research on the subject of automatic surface reconstruction should involve automatic quality control of the results. Such quality control, although will not solve all the problems, will improve the reliability of the DEM (for An in-depth discussion on the subject, see Krupnik, 1998).

Based on the results of this research, it is possible to conclude that automatic generation of DEM from SPOT images, using commercial software, is feasible. Nevertheless, special attention should be paid, and interactive control should be performed in areas known to have the problematic land cover characteristics.

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ACKNOLEGMENTS

This research was supported by the Israeli Ministry of Science and the Arts through Israel Space Agency.

The research was also supported by the Fund for the Promotion of Research at the Technion and the Winnipeg Research Fund.

SPOT processing software courtesy of TRIFID Corp., St. Louis, MO, USA; MATCHT software courtesy of INPHO, Stuttgart, Germany; Digital photogrammetry software courtesy of Intergraph Corp., Huntsville, AL, USA.

The author would also like to thank:

- Eastronics Ltd., for their help with software integration and the contact with Intergraph;
- The Survey of Israel, for providing aerial photographs;
- ADM, for scanning the aerial photographs.