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SYSTEM CALIBRATION, GEOMETRIC ACCURACY TESTING AND VALIDATION OF DEM & ORTHOIMAGE DATA EXTRACTED FROM SPOT STEREOPAIRS USING COMMERCIALLY AVAILABLE IMAGE PROCESSING SYSTEMS

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ABSTRACT.

The paper describes the comprehensive testing of the digital photogrammetric modules forming parts of the image processing systems available from a number of remote sensing system suppliers - PCI, ERDAS, R-WEL, etc. - for use with SPOT stereo-pairs. The tests have been conducted over a large area of 12,000 sq.km forming part of the Badia, a desert area located in the north-east of Jordan that is covered by a block of five SPOT stereo-pairs. The terrain data available for calibration and testing has included a very high accuracy test field comprising 130 ground control points, whose positions and heights have been established using differential GPS. This is supplemented by 150km of profile data measured using real-time kinematic GPS and by digitized contour data derived from existing 1:50,000 and 1:250,000 scale topographic maps of the area produced using aerial photogrammetric techniques.

The results of a comprehensive series of geometric accuracy tests are given for both Level 1A and 1B image data. This is followed by the results of a series of tests to validate the DEMs and the contours derived from the elevation data produced by each of the packages that have been tested. The final results from this validation are surprisingly good, but only after extensive use of filtering techniques to remove the artefacts and spurious features generated by the image matching routines employed by the different systems. The results achieved during tests of the individual orthoimages and the orthoimage mosaics produced using the SPOT DEM data sets are also given, both in terms of their radiometric quality and their geometric accuracy.

This comprehensive series of tests revealed a number of flaws and shortcomings in all of the image processing systems that have been calibrated and tested. Some of the more serious flaws are described and discussed in the paper. The findings from the tests resulted in the flawed parts of the various systems being modified and then re-tested via a highly interactive interchange of programs and data between the authors and the system suppliers - to the benefit of future users of these systems. The test area, having proven its worth, is available for testing of other space image data - including that from the forthcoming commercial high-resolution satellites - in a similar manner to that described in the paper.

1 INTRODUCTION

In terms of its value to the topographic mapping community, the SPOT satellite with its cross-track stereo-coverage and 10m ground pixel size can be regarded as the only really operational satellite imaging system. However, notwithstanding its availability since the launch of the first satellite in the SPOT series in 1986, it has only been used in a production environment in a fairly limited way for small-scale mapping by a relatively small number of national mapping agencies. Till recently, their efforts have mainly been concentrated in the arid and semi-arid environment of North East Africa and South West Asia lying around the Red Sea and Gulf of Aden where data acquisition is not impeded by cloud cover. The methods used by these agencies to extract the planimetric detail and contours from SPOT stereo-pairs have followed classical photogrammetric lines comprising manual/visual measurements by an operator using an analytical plotter, the final product being the traditional type of vector line map. Examples are the mapping of Djibouti at 1:50,000 and 1:200,000 scales by IGN (Veillet, 1990, 1992) and of North East Yemen at 1:100,000 scale by OSI (Murray & Gilbert 1990; Murray & Newby 1990). Even in EMA's work producing 1:50,000 scale orthoimages of Ethiopia, the measurements of the DEM are carried out manually by an operator using profiling techniques (Medhin, 1993).

Early efforts to utilize purely digital techniques with automatic image matching for the extraction of high density DEMs from SPOT stereo-pairs did not yield good results. Thus, for example, in the tests carried out by Brockelbank and Tam (1991) using Landscan software, the validation of the DEMs for the DMN and Red Deer stereo-models resulted in RMSE values in height of ±16.8 and ±11.8m respectively. For the two tests of the DEM data produced from SPOT stereo-pairs by the STX Corporation that were carried out by Sasowsky et al (1992) and by Bolstad & Stove (1994), the RMSE values were only slightly better. Finally, for the test carried out by Giles & Franklin (1996) using DEM data generated by the HI-VIEW package, the RMSE in elevation of the tested points was ±21.6m. These figures certainly did not compare well with the figures obtained during the validation of DEM data obtained using analytical plotters - e.g. those by Gugan & Dowman (1988), Theodossiou & Dowman (1990) and Akiyama (1992) with RMSE values of ±8.6m, ±5.7m, and ±8.8m (in flat terrain) & ±15.8m (in mountainous terrain) respectively. On the other hand, while the utilization of analytical plotters has ensured a relatively high accuracy in height, the use of purely manual/visual measurements in these instruments means that only comparatively few points can be measured with a wide grid interval between them. Otherwise the collection of the DEM data takes too long and the procedure becomes uneconomic.

However, over the last two or three years, a completely new generation of software has appeared on the market that will handle SPOT stereo-pairs in digital form to produce DEMs and ortho-images using automatic image matching techniques. These software packages or modules have been produced

(i) by the mainstream photogrammetric suppliers on some of their digital photogrammetric workstations - e.g. from LH Systems (as part of its SOCET SET suite); Intergraph (Trifid Package) and VirtuoZo;
(ii) by some of the main remote sensing system suppliers - PCI (EASI/PACE and now OrthoEngine); ERDAS (OrthoMAX); MicroImages (TNT-mips); etc.; and
(iii) by smaller specialist suppliers - R-WEL (DMS); DVP; etc., - that have developed from university departments active in the area of remote sensing and the mapping sciences.

Arising from this development, there is a need and a strong interest both from the mapping community and from the geoscience, geophysical and geoexploration communities in having these new software modules evaluated. Such an evaluation should place a particular emphasis on the validation of the accuracy of the geospatial data that these systems can generate.

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Till now, the only substantial study of this type that has been undertaken is that by Trinder et al (1994). This mainly tested and evaluated research software produced by three university groups (UCL, UNSW and Graz), but it also included two of the commercial packages (ERDAS and HAI) in its programme of tests. Recently (since 1996), the opportunity has arisen at the University of Glasgow to carry out a further programme of tests over a newly established test field in the Badia area in North East Jordan. This paper gives a report on some of the results achieved and the experiences gained as a result of these tests.

2 TEST SITE AND REFERENCE MATERIAL

The test site that has been used covers the whole of the area of the Badia Project under which a group of British and Jordanian scientists are undertaking a wide-ranging inter-disciplinary study of part of the "panhandle" of North East Jordan. The area covers 12,000 sq. km. and mainly comprises a stony desert with much of its surface being covered by basaltic lava flows. The terrain has little or no vegetation, though the north western part of the area has a few villages around which is some marginal agriculture with some scattered fields. A prominent bare ridge crosses the middle of the area from north to south while parts of the southern area bordering Saudi Arabia comprise large salt pans.

The Royal Jordanian Geographic Centre (RJGC) - which is Jordan's national mapping organisation - has collaborated with the authors to establish the following reference data sets which have been used to carry out an extensive series of tests of the data derived from the five SPOT stereo-pairs that cover the area.

(i) A network of 130 ground control points (GCPs) has been established using five of the latest Ashtech dual-frequency, geodetic quality GPS sets to carry out the field survey employing differential GPS methods. 60 of these points have been located in a single stereo-model (122/285) designated as a special reference scene. The remaining 70 points have been distributed as evenly as possible over the remaining four models so that between 15 and 20 GCPs are available in each model. The estimated accuracies of each of these points is $\sigma_E = \sigma_N = \sigma_H = \pm 1$m.

(ii) In addition, the RJGC has measured accurate elevation profiles along 150 km of the two old roads crossing the area (now replaced by modern highways). Kinematic GPS techniques were used to measure the profiles employing the same geodetic quality sets used to establish the coordinates of the GCPs. This provided 15,000 height points that could be used for the validation of the DEM elevation data extracted from the SPOT stereo-pairs.

(iii) Also digitized versions of the existing 1:50,000 and 1:250,000 scale contoured topographic maps of the area were made available by the RJGC. These had been produced originally in the U.S.A. under an American aid programme using aerial photogrammetric techniques for the production of the basic 1:50,000 scale coverage. Again this data could be used to validate the DEM data generated from the SPOT stereo-pairs.

3 SYSTEMS TESTED AND THEIR CHARACTERISTICS

Five commercially available digital photogrammetric systems having the capability of handling SPOT stereo-pairs have been tested using these GCPs and reference data sets. These comprise the following:-

(i) the PCI EASI/PACE system running on a PC under the Microsoft Windows OS;
(ii) the OrthoMAX module of the ERDAS Imagine system running on Sun and SGI graphic workstations under the Unix OS;
(iii) the R-WEL DMS system running on a PC under MS-DOS;
(iv) the MicroImages TNT-mips system running on a PC under Windows; and
(v) the VirtuoZo system running on an SGI graphics workstation under the Unix OS.

To our astonishment, not one of these packages would run properly with the SPOT test data when first tested - for a wide variety of different reasons. Thus quite a number of modifications - some minor; others quite major - had to be made to each of the systems before they could be used in the tests. In fact, the authors have only recently been informed by the European agents that the required modifications to the VirtuoZo system have now been made, but this news has come too late for the system to be included in the present test programme. In the case of TNT-mips, again according to the European agents, the necessary changes are still being carried out. Thus the tests have had to be restricted to the three systems - EASI/PACE; DMS: and OrthoMAX - that have been modified.

Of these, both EASI/PACE and OrthoMAX employ a somewhat similar solution based on an initial modeling of the orbital track based on the ephemeris data supplied as a header file with the SPOT image data. This provides the coordinates of the perspective centres for each individual line of the SPOT image and the corresponding attitude data. The photogrammetric solution then employs classical analytical methods based on the use of 3D collinearity equations, albeit modified for use with linear array imagery where each ray direction is constrained to lie within a specific plane. By contrast, the DMS approach first uses a 2D polynomial procedure to rectify and fit the individual SPOT images planimetrically to the GCPs in the terrain system. This operation is followed by the measurement and computation of the terrain elevation values using simple parallax heighting formulae. Then, with all three systems, a digital elevation model (DEM) is produced using automatic image matching procedures based on the use of an area-based correlation technique. The resulting data set then forms the basis for the production of contours and for the generation of the corresponding ortho-image from one of the component images of the SPOT stereo-pair.

4 GEOMETRIC ACCURACY TESTING

It was found during initial testing of the EASI/PACE system that, while it ran correctly with Level 1A stereo-imagery, it gave poor results with the corresponding Level 1B imagery. However a rapid response was received from PCI and the system was rapidly modified to handle the Level 1B imagery which then gave good results (Al-Rousan et al 1997). In the case of the OrthoMAX system, while it could also handle the Level 1A stereo-imagery, at the time of the tests, it could only cope with Level 1B imagery produced before the autumn of 1995 when SPOT Image changed its processing and format. It could not deal with data in this new format. (In this respect, we have just been informed that the necessary changes have at last been made). Finally DMS has been designed from the outset to process Level 1B imagery only and so it does not handle Level 1A imagery. All of these initial findings have of course constrained the test programme.

D. Fritsch, M. Englich & M. Sester, eds, 'IAPRS', Vol. 32/4, ISPRS Commission IV Symposium on GIS - Between Visions and Applications, Stuttgart, Germany.

4.1 Results Achieved Using the Special Reference Model.

Starting with the results of the geometric accuracy testing carried out after the absolute orientation of the stereo-model using the special reference scene (122/285), these are summarized in Table I for both the Level 1A and Level 1B stereo-models. Different numbers and combinations of control points and independent check points have been used in these tests.

(I) Level 1A - Scene 122/285

A. EASI/PACE	Control Points				Check Points				
No.	ΔE (m)	ΔN (m)	ΔPl (m)	ΔH (m)	No.	ΔE (m)	ΔN (m)	ΔPl (m)	ΔH (m)
47	±4.2	±4.2	±5.9	±4.8	0	-	-	-	-
32	±5.2	±6.4	±8.2	±6.0	15	±5.2	±5.9	±7.9	±6.6
22	±3.8	±4.8	±6.1	±4.1	25	±4.9	±4.6	±6.7	±6.4
12	±3.9	±4.1	±5.7	±4.6	35	±4.6	±5.1	±6.9	±6.1
B. OrthoMAX									
47	±3.7	±3.8	±5.3	±1.5	-	-	-	-	-
28	±3.7	±4.0	±5.4	±1.5	-	-	-	-	-
22	±3.9	±4.7	±6.1	±1.2	-	-	-	-	-

(II) Level 1B - Scene 122/285

A. EASI/PACE	Control Points				Check Points				
No	ΔE (m)	ΔN (m)	ΔPl (m)	ΔH (m)	No.	ΔE (m)	ΔN (m)	ΔPl (m)	ΔH (m)
45	±4.7	±4.9	±6.8	±4.7	0	-	-	-	-
33	±4.2	±5.6	±7.0	±4.8	15	±7.3	±5.1	±8.9	±5.3
23	±4.8	±5.0	±6.9	±4.5	25	±5.3	±6.1	±8.0	±5.8
13	±3.3	±4.6	±5.7	±3.5	35	±6.0	±5.9	±8.4	±5.7
B. OrthoMAX									
49	±12.5	±7.8	±14.7	±1.0		-	-	-	-
39	±6.3	±4.7	±7.9	±1.3		-	-	-	-
C. DMS									
45	±8.4	±7.8	±11.5	±4.5	-	-	-	-	-
30	±8.7	±7.9	±11.8	±4.8	15	±8.1	±8.1	±11.5	±6.7
20	±9.5	±8.5	±12.8	±4.5	25	±8.7	±8.1	±11.9	±6.2
10	±8.5	±8.0	±11.9	±5.9	35	±10.8	±9.1	±13.5	±5.2

Table I Results of the accuracy tests for the reference scene (122/285) giving the RMSE values of the residual errors in planimetry and height at the control points and check points for Level 1A and 1B stereo-pairs after absolute orientation using the three tested systems.

4.2 Results Achieved with the Other Stereo-Models

For the remaining four scenes (123/285, 123/286, 124/285, 124/286), only Level 1B stereo-pairs could be used (i.e. the corresponding Level 1A stereo-pairs were not available) and, as noted above, a much smaller number of GCPs were available. Also the first two of these stereo-models (123/285 and 123/286) could not be handled by the OrthoMAX system since the individual images had been processed by SPOT Image in the new post-1995 (CAP) format. The results obtained in the geometric accuracy tests with these four additional stereo-pairs are given in Table II on the next page.

4.3 Analysis of the Results of the Geometric Accuracy Tests.

From Table I, it can be seen that the differences in the results that have been achieved between the Level 1A and the Level 1B stereo-pairs are mostly quite small and hardly significant. This is quite an important point since, in previously published figures comparing the results of tests of Level 1A and 1B stereo-pairs, e.g. those by Gugan and Dowman (1988), the Level 1B results were invariably much poorer. Looking next at the results for planimetric accuracy, the RMSE values for EASI/PACE and OrthoMAX (- with the single exception of the ±14.7m obtained with one of the OrthoMAX tests -) lie in the range of ±5 to 8m at the control points and ±6 to 9m at the check points. Those obtained with the DMS system are slightly greater, lying in the range ±11 to 14m at both the control points and check points.

With regard to the height accuracy, in the case of the EASI/PACE and DMS systems, these are consistently of a high quality with average RMSE values in the range ±5 to 7m at both the control points and check points. On the other hand, the height accuracy figures obtained with OrthoMAX are simply not believable. The RMSE values lie in the range ±1 to 1.5m in the case of the tests of the stereo-pairs for the reference scene 122/285 and ±0.016 and ±0.018m for the only two other Level 1B pairs with the older format that could be handled by OrthoMAX. Protracted correspondence with the originators of the package (Vision International) has so far failed to produce an explanation for this phenomenon.

D. Fritsch, M. Englich & M. Sester, eds, 'IAPRS', Vol. 32/4, ISPRS Commission IV Symposium on GIS - Between Visions and Applications, Stuttgart, Germany.

System	Scene No. & Format	No. of Control Points	RMSE Values at Control Points				No. of Check Points	RMSE Values at Check Points			
			ΔE (m)	ΔN (m)	ΔPl (m)	ΔH (m)		ΔE (m)	ΔN (m)	ΔPl (m)	ΔH (m)
EASI/PACE	123/285 1B	13	±3.5	±3.8	±5.2	±6.7	10	±4.2	±5.5	±6.9	±5.1
DMS	123/285 1B	9	±10.0	±9.3	±13.7	±11.6	10	±14.5	±17.6	±22.8	±6.6
EASI/PACE	123/286 1B	14	±4.2	±3.9	±5.7	±3.3	15	±4.6	±7.6	±8.9	±6.2
DMS	123/286 1B	13	±10.1	±5.9	±11.7	±4.9	15	±14.1	±9.9	±17.2	±7.0
EASI/PACE	124/285 1B	19	±4.1	±5.0	±6.5	±5.4	0	-	-	-	-
	124/285 1B	11	±3.3	±5.9	±6.8	±5.8	8	±5.5	±4.6	±7.2	±5.2
OrthoMAX	124/285 1B	18	±3.1	±4.5	±5.5	±0.016	-	-	-	-	-
DMS	124/285 1B	16	±10.1	±7.9	±12.8	±5.1	-	-	-	-	-
	124/285 1B	8	±6.0	±8.1	±10.1	±7.5	8	±18.4	±8.7	±20.3	±7.0
EASI/PACE	124/286 1B	13	±3.6	±4.9	±6.1	±5.8	-	-	-	-	-
OrthoMAX	124/286 1B	14	±3.4	±3.2	±4.7	±0.018	-	-	-	-	-
DMS	124/286 1B	13	±11.2	±8.5	±14.1	±7.0	-	-	-	-	-

Table II Results of the accuracy tests giving the RMSE values in planimetry and height at the control points and check points of the other four Level 1B stereo-pairs of the Badia area after absolute orientation using the EASI/PACE, OrthoMAX and DMS systems.

With regard to the overall excellent results achieved with the Level 1B stereo-pairs, comparison may be made with the best previously published figures for accuracy known to the authors by Yeu et al (1992) which gave RMSE values of ±14.0m in planimetry and ±13.8m in height.

Taking a still wider view, the results achieved with the Level 1A stereo-pair compare very favourably with the best published figures for comparable tests using analytical plotters. For example, those by Rodriguez et al (1988) gave RMSE values of circa ±10m in planimetry and ±4 to 7m in height; Kratky (1988) obtained ±7 to 10m in planimetry and ±3 to 8m in height; and Gugan & Dowman (1988) ±15 to 17m in planimetry and ±5.5 to 8.5m in height. Thus the newly modified digital systems are capable of similar accuracies.

Again looking still further afield, another remarkable feature is that, with digital systems, the very best figures appear to come from those packages (CARTOSPOT, DVP, EASI/PACE) that are based on the modeling and photogrammetric solution that has been devised and developed by Toutin of CCRS. Thus using CARTOSPOT (Toutin & Carbonneau 1990), the respective RMSE values were ±5 to 6m (in plan) and ±3 to 3.5m (in height) respectively. Using the DVP system, Toutin & Beaudoin (1995) achieved ±6.2m (in plan) and ±3.7m (in height), while using EASI/PACE, Cheng & Toutin (1995) obtained ±4.7m (in plan only). To these can be added the figures obtained for EASI/PACE in the present series of tests which have been set out in more detail in the paper by Al-Rousan et al (1997).

5 VALIDATION OF THE DEM DATA PRODUCED BY THE DIFFERENT SYSTEMS.

A series of accuracy tests have been carried out to validate the elevation data generated by the various systems using automatic image matching techniques. These have used different reference data sets - the GCPs; the elevation profiles measured using kinematic GPS techniques; and the digitized contours available from the existing topographic maps.

5.1 Comparative Height Accuracy at the GCPs

This particular test involved a comparison of the given elevation values of the GCPs with the corresponding values at those points generated by the image matching procedures for the DEM. Thus the DEM elevation values are those determined purely from the disparities generated during the image matching operation. This particular test has been carried out for all the SPOT stereo-pairs. Table III gives a summary of the RMSE values obtained for both the Level 1A and 1B stereo-pairs over the special reference scene 122/285.

(I) Level 1A - Scene 122/285

System	Scene/ Format	RMSE of DEMs at the Control Points		RMSE of DEMs at the Check Points	
		No.	Δ H (m)	No.	Δ H (m)
A. EASI/PACE	122/285 1A	31 25 10	±3.8 ±4.0 ±4.5	15 20 36	±4.3 ±3.4 ±3.5
B. OrthoMAX	122/285 1A	28	-	25	±5.2

(II) Level 1B - Scene 122/285

D. Fritsch, M. Englich & M. Sester, eds, 'IAPRS', Vol. 32/4, ISPRS Commission IV Symposium on GIS - Between Visions and Applications, Stuttgart, Germany.

System	Scene/ Format	RMSE of DEMs at the Control Points		RMSE of DEMs at the Check Points	
		No.	Δ H (m)	No.	Δ H (m)
A. EASI/PACE	122/285 1B	47 32 22 12	±3.7 ±2.4 ±3.8 ±3.7	- 15 25 35	- ±3.3 ±3.7 ±3.6
B. OrthoMAX	122/285 1B	39	±-1.0	25	±5.6
C. DMS	122/285 1B	45 29 19 14	±4.5 ±4.8 ±4.5 ±5.9	- 15 25 35	- ±6.7 ±6.2 ±5.2

Table III Accuracy tests of the elevation values obtained from the DEMs at the control and check points for the reference scene (122/285) compared with the given values determined by GPS.

From the results it can be seen that much the same accuracy figures were obtained at the control points and the check points for both the Level 1A and Level 1B stereo-pairs. The figures obtained by the EASI/PACE system are consistently the best, but those obtained using DMS and OrthoMAX are only slightly less good. It is especially interesting to note that the elevation values from the DEM produced by the OrthoMAX system gave quite sensible values in contrast to those obtained in the absolute orientation mentioned in Section 4.3 above.

Table IV gives the results obtained for the remaining four scenes for which only Level 1B stereo-pairs were available. Because of the difficulties experienced with the OrthoMAX system handling the Level 1B stereo-pairs, the tests have been confined to the EASI/PACE and DMS systems.

System	Scene/ Format	RMSE of Elevation Values at the Control Points		RMSE of Elevation Values at the Check Points	
		No.	Δ H (m)	No.	Δ H (m)
EASI/PACE	123/285 1B	16 9	±4.7 ±5.9	- 10	- ±3.3
DMS	123/285 1B	8	±11.6	10	±6.6
EASI/PACE	123/286 1B	29 18 15	±2.6 ±3.9 ±4.9	- 11 14	- ±3.7 ±3.9
DMS	123/286 1B	12 12	±4.9 ±4.1	15 18	±7.0 ±5.8
EASI/PACE	124/285 1B	16 8	±6.0 ±4.8	- 8	- ±6.2
DMS	124/285 1B	16 8	±5.1 ±7.5	- 8	- ±7.0
EASI/PACE	124/286 1B	11	±5.8	-	-
DMS	124/286 1B	16	±6.0	**-**	**-**

Table IV Accuracy tests of height at the control and check points of the other Level 1B stereo-pairs using the DEM data extracted by the EASI/PACE and DMS systems.

5.2 Comparison of DEM Values v. GPS Profile Values

This has involved the comparison of a much larger sample of the elevation values from the DEMs with the corresponding values given by the GPS profiling carried out along the old main roads crossing four of the five SPOT Level 1B stereo-pairs. The results are given in Table V on the next page.

The best accuracy figures of ±6m in terms of the standard deviation values in elevation were obtained using the EASI/PACE system, followed by the OrthoMAX and DMS systems for which the corresponding values were quite close at ±8.4m and ±9.2m respectively. Obviously these figures obtained in the comparison with the kinematic GPS elevation values using a large sample are somewhat less good than those obtained at the restricted number of GCPs where the reference elevation values have been obtained using GPS in a static mode.

System	Scene/ Format	No. of Points	Mean (m)	Standard Deviation Δ H (m)
EASI/PACE	122/285, 123/285, 124/285 122/285 1B	1,248 528	24.0 24.0	±6.1 ±6.0
DMS	122/285, 123/285, 124/285 122/285 1B	1,248 528	25.6 15.6	±9.3 ±9.0
OrthoMAX	122/285 1B	528	22.4	±8.4

Table V Height accuracy in the DEMs produced by different systems using GPS profile data. s

D. Fritsch, M. Englich & M. Sester, eds, 'IAPRS', Vol. 32/4, ISPRS Commission IV Symposium on GIS - Between Visions and Applications, Stuttgart, Germany.

5.3 Comparison of DEM Values v. Values Given by Contours from Existing Maps

The first comparison has been made with the digitized contours of the 1:50,000 scale map at 10m interval produced by aerial photogrammetric methods. The digitized photogrammetric contours were superimposed over the DEM data set and the respective elevation values were compared for selected contours. For the reference scene 122/285, the RMSE values are summarized in Table VI for both the Level 1A and 1B stereo-pairs.

System	Scene/ Format	Contour Interval (m)	No. of Points Measured	RMSE ΔH (m)
EASI/PACE	122/285 1A	10	257	±6.2
	122/285 1B	10	257	±4.9
DMS	122/285 1B	10	220	±8.1
OrthoMAX	122/285 1B	10	325	±8.9

Table VI The accuracy of height in the DEMs produced by different systems by comparison of heights given by the digitized contours @ 10m interval from the 1:50,000 scale reference map with the height values given by the Level 1A and 1B DEMs.

Inspection of the RMSE values in elevation from all three systems shows a very small range of values between the respective results for the Level 1A and 1B stereo-pairs. Also there is only a relatively small range of values between the three systems with EASI/PACE once again giving the best results. A second comparison has been made using the 50m contours from the 1:250,000 scale map for the reference scene (122/285) using both the Level 1A and 1B elevation data. The results are given in Table VII below.

System	Scene/ Format	Contour Interval (m)	No. of Points Measured	RMSE ΔH (m)
EASI/PACE	122/285 1A	50	531	±8.0
OrthoMAX	122/285 1A	50	398	±9.2
EASI/PACE	122/285 1B	50	719	±7.0
OrthoMAX	122/285 1B	50	712	±8.9
DMS	122/285 1B	50	589	±9.9

Table VII Height accuracy in the Level 1A and 1B DEMs produced by the systems by comparison of the height values given by the digitized contours @ 50m interval from the 1:250,000 scale reference map with the height values given by the DEMs.

Inspection of the RMSE results show that only slightly poorer results were obtained from this comparison than were obtained from the comparison with the contours from the 1:50,000 scale sheet. It appears that, in accuracy terms, little was lost in the reduction of scale between the 1:50,000 and 1:250,000 scale maps.

For the other four scenes, comparisons could only be made with the digitized contours from the 1:250,000 scale sheet of the area having a 50m interval (but having been derived from the 1:50,000 scale sheets). The RMSE values are summarized in Table VIII. It will be seen that these are in the same range as those achieved with the special reference scene 122/285.

System	Scene/ Format	Contour Interval (m)	No. of Points Measured	RMSE ΔH (m)
EASI/PACE	123/285 1B	50	442	±8.1
DMS	123/285 1B	50	325	±10.8
EASI/PACE	123/286 1B	50	403	±6.1
DMS	123/286 1B	50	449	±12
EASI/PACE	124/285 1B	50	443	±6.5
DMS	124/285 1B	50	279	±7.3
OrthoMAX	124/285 1B	50	387	±5.2
EASI/PACE	124/286 1B	50	410	±7.8
DMS	124/286 1B	50	348	±7.8
OrthoMAX	124/286 1B	50	453	±8.4

Table VIII The RMSE values in elevation for the DEMs of the other stereo-pairs covering the Badia area using 50m contours from the 1:250,000 scale map.

It should be said that, prior to carrying out the comparisons made to validate the DEM data, contour plots had been constructed from the elevation data generated from each stereo-model by each of the systems tested. These revealed that, although there were very few gaps or holes in the elevation data, there were quite a number of small artefacts which mostly revealed themselves in the form of tiny circular features that were not present on the ground. These were removed through the use of the filtering routines that are available in the EASI/PACE and OrthoMAX packages. A similar operation had to be carried out for the elevation data generated by DMS using third-party contouring software. Once this had been done, there was mostly a very good agreement between the reference set of contours and those generated from the DEMs for all of the packages that were tested.

D. Fritsch, M. Englich & M. Sester, eds, 'IAPRS', Vol. 32/4, ISPRS Commission IV Symposium on GIS - Between Visions and Applications, Stuttgart, Germany.

6 VALIDATION OF THE ORTHOIMAGE DATA PRODUCED BY THE DIFFERENT SYSTEMS

A test of the planimetric accuracy of the final orthoimages has been carried out for the reference stereo-model using both the Level 1A and 1B stereo-pairs with the different systems. This utilized a simple linear conformal transformation for this comparison of the image positions of the GCPs measured on the orthoimages with the high accuracy coordinates obtained in the field using GPS. A summary of the results is given in Table IX.

System	SPOT Scene and Format	Pixel Size (m)	No. Of Check Points	RMSE in Pixels			RMSE in Metres		
				Δx	Δ y	ΔPl	Δ X	Δ Y	ΔPl
EASI/PACE	122/285 1A	20	40	±0.46	±0.48	±0.67	±9.1	±9.7	±13.3
	122/285 1B	20	43	±0.44	±0.44	±0.60	±8.7	±8.8	±12.3
OrthoMAX	122/285 1A	20	40	±0.52	±0.57	±0.77	±10.5	±11.4	±15.5
	122/285 1B	20	43	±0.67	±0.58	±0.89	±13.4	±11.7	±17.7
DMS	122/285 1B	20	38	±060	±0.53	±0.80	±12.1	±10.6	±16.0

Table IX Accuracy tests of the orthoimages produced from the Level 1A and 1B stereo-models for the reference scene (122/285) by the various systems.

As can be seen from the table, a 20m pixel has been used to produce orthoimages from all three systems. The RMSE values at the GCPs lie in the range ±9 to 13.5m in terms of terrain coordinate values (or ±S0.45 to 0.7 pixel in terms of image coordinates). The best figures were those obtained by EASI/Pace, with those from DMS and OrthoMAX being only slightly less good. The orthoimages from all three systems would met the planimetric specification for 1:50,000 scale topographic mapping where the standard error of 0.3mm is equivalent to 15m on the ground. The radiometric quality of all the orthoimages was excellent and they all merged smoothly to produce the final orthoimage mosaic.

7 CONCLUSION

From the extensive series of tests described above, certain general remarks can be made as follows:-

(i) There is a need for an independent evaluation to be made of each software package or system to ensure that it is properly calibrated and is fully functional from the users' point of view. The comprehensive series of tests conducted by the authors showed up some important flaws that resulted in parts of all the systems having to be modified and then re-tested via a highly interactive interchange of programs and data conducted over the Internet – to the benefit of users of the systems.

(ii) The establishment of a high-quality test field in the Badia area designed specifically for use with satellite stereo-imagery has shown its worth and is available for the geometric accuracy testing and validation of the DEMs and ortho-images that will be generated from the forthcoming high-resolution satellite imagery using the new software .that will be needed to handle along-track and flexibly pointing stereo-imagery.

(iii) The software systems that have been tested can all generate high-density DEMs and ortho-images from SPOT stereo-pairs to an accuracy standard appropriate to small-scale topographic mapping. Besides national mapping organizations, this may have a special importance to those in the geoscience, geophysical and geo-exploration communities working in remote areas where maps may not be available. For them, the use of Level 1B stereo-pairs is of special interest: the tests have shown that the results from these images are as good as those from the Level 1A imagery favoured by the photogrammetric community up till now.

(iv) Up till now, most national mapping organizations that have been involved in topographic mapping from SPOT stereo-pairs have utilized analytical plotters in conjunction with hard copy images to generate classical vector-type line maps. On the basis of the tests reported in this paper and those carried out by Trinder et al (1994), it does seem that the current generation of digital photogrammetric systems using automated image matching techniques are now capable of generating DEMs, contours and orthoimages to a high degree of accuracy by the standards possible with SPOT stereo-pairs. At the same time, the automated method is much faster and so the cost of acquisition of the terrain data is much reduced. However this is based on the availabilty of high quality ground control points and images with a good base-to-height ratio.

(v) Of course, the remarks made in (iv) only apply where the terrain is really suited to the application of automated image matching techniques – which has been the case in the area of stony desert with little vegetation used for the tests. In other areas with large areas of vegetation or steep slopes that are less suited to the use of such matching techniques, the results may not be so favourable. Other difficulties could also arise in areas where there are considerable changes in the vegetation cover, cultivated areas or hydrology between seasons, giving rise to substantial differences in the appearance of a specific area on the individual scenes making up the stereo-pair. In such circumstances, it may be impossible to carry out the image matching procedure successfully over large parts of the area covered by the stereo-pair.

(vi) Besides the accuracy issues that have been the principal concern of the tests reported in this paper, it is also necessary to keep in mind the limited ground resolution of the SPOT images. With its 10m ground pixel size, it is still substantially deficient in providing the detail required for the production of a full final edition of a topographic map at 1:50,000 scale. Petrie and Liwa (1995) have shown that this can be in the order of 30% of the required detail for areas tested in Eastern, Central and Southern Africa. In order to overcome this deficiency, an additional comprehensive field completion operation will need to be undertaken.

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