EARSeL Advances in Remote Sensing
Vol. 5. pp 11-29

Topographic mapping of arid and semi-arid areas in the Red Sea region from stereo space imagery

G. Petrie, N. Al-Rousan, A.H.A. El-Niweiri, Z. Li, and M.J. Valadan Zoej
Department of Geography & Topographic Science
University of Glasgow

Fax: +44 (0) 141 330 4894

ABSTRACT

This paper presents the results of a series of geometric accuracy tests of stereo space images carried out over various sites in the Red Sea region in the context of topographic mapping of the area. These include tests of the planimetric and elevation accuracies of MOMS-02 along-track scanner images and of MC and LFC photographs conducted over test sites in Sudan. Besides these tests, further tests have been carried out to validate the DEM and orthophotographs produced from an MC stereo-pair of part of the Red Sea Hills in Sudan. In the Badia area of North East Jordan, a special high accuracy test field has been established based on a network of ground control points fixed by Differential GPS. This has been used to create a very large DEM and orthoimage mosaic for the area using five SPOT Level 1B stereo-pairs. The results of extensive tests of the accuracy of point determination and of the DEM, contours and orthoimages created for the Badia Project are given. The final conclusion is that the use of stereo space imagery for topographic mapping in the Red Sea region can produce useful results provided that the limitations in the accuracy of the elevations derived from such images are recognised. However the main deficiencies lie in the extent of the detail and the information content that can be extracted from present day space imagery.

1. INTRODUCTION

The area of North East Africa and South West Asia bordering the Red Sea and Gulf of Aden (Figure 1) is mostly a harsh, sparsely populated and inhospitable land comprising extensive areas of sandy and stony desert and rugged mountainous terrain, which poses special difficulties for those concerned with the mapping of its topography and geology. Not only is most of its area sparsely populated, but its communications networks are poorly developed, overland travel often being slow and quite exhausting to undertake. Access to the many remote areas requiring mapping is often very poor and the maintenance of field parties in such areas can cause severe logistical problems. Indeed operations to carry out ground control surveys and field completion will often have to be conducted on an expedition-style basis, as will be the case with any associated geological or geophysical field work.

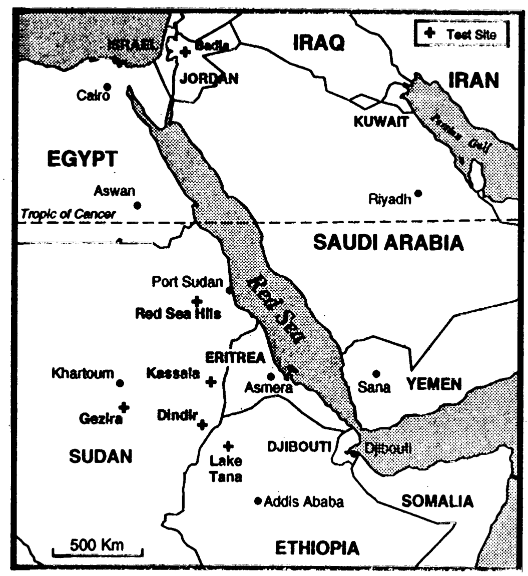

Figure 1: Location of test sites in the Red Sea region

Thus the mapping of the areas of North Eastern Africa and South Western Asia bordering the Red Sea has presented a formidable challenge to both the topographic scientist and the geoscientist. While initially over the first half of this Century this huge and difficult area was only mapped at very small scales - often in a rudimentary and fragmented fashion via route surveys - over the last 25 to 30 years, the situation has changed radically and quite extensive topographic map coverage now exists for many countries in the region - though there are still some major areas where the coverage is either seriously deficient or does not exist at all. While the primary method of mapping has been based on aerial photogrammetric techniques, over the last ten years, a considerable amount of topographic mapping has been carried out using satellite imagery. Indeed it would be true to say that more satellite mapping has been conducted in this region than in any other part of the world. This paper outlines these mapping efforts and reports on some of the experimental work and mapping projects in the Region based on the use of satellite imagery that have been carried out at the University of Glasgow.

2. TOPOGRAPHIC MAPPING IN THE RED SEA REGION

In North East Africa, the situation regarding topographic map coverage is very mixed, at least partly the result of the many conflicts that have afflicted the area in recent years. Some countries such as Egypt have extensive coverage, although substantial parts need revision. Perhaps unexpectedly, Somalia has 100% coverage executed by Russian mapping agencies in the 1970s. However, in other countries, the situation is mostly one of poor coverage, more especially in the Sudan (with only 10% cover), Ethiopia (40%) and Eritrea (5%) (Petrie 1997). By contrast, in South West Asia, there is extensive existing map coverage of good quality, e.g. in Israel, Jordan, Saudi Arabia and Yemen, there is complete cover, the major problem being that of the map revision of very large numbers of maps - 2,300 individual sheets in the case of Saudi Arabia's basic topographic map series at 1:50,000 and 1:100,000 scales. However in many of the countries lying on both sides of the Red Sea, access to existing maps can be very difficult due to security restrictions arising from the numerous conflicts that have afflicted the Region over the last sixty years. This causes geoscientists to look at other sources of topographic data such as that which can be extracted from satellite imagery.

3. SATELLITE MAPPING IN THE RED SEA REGION

SPOT stereo-imagery has been used quite extensively for original mapping, e.g. at 1:100,000 scale in North Yemen by Ordnance Survey International (OSI) (Murray & Newby 1990, Murray & Gilbert 1990) and at 1:200,000 scale and 1:50,000 scale in the small territory of Djibouti by the French Institut Geographique National (IGN) (Veillet 1990, 1992). Currently it is being employed in certain parts of Ethiopia for the production of 1:50,000 scale orthoimage maps by the Ethiopian Mapping Authority (EMA) (Jobre 1993, Medhin 1993, 1995). Furthermore revision of 1:250,000 scale topographic mapping of the sensitive border areas of Saudi Arabia by its Military Survey Department (MSD) is also being carried out from SPOT stereo-imagery. Almost all of this mapping and map revision in these various countries has been based on the use of analytical plotters in conjunction with hard copy SPOT stereo-images; only a very limited use of digital photogrammetric workstations has occurred up till now (Al-Rousan et al 1997).

4. TESTS OF GEOMETRIC ACCURACY AND INFORMATION CONTENT IN SUDAN

During the late 1980s, a large number of tests have been carried out over various sites in the Sudan to establish the geometric accuracy and the information content of topographic maps that can be derived from different types of satellite imagery. These tests have involved Landsat MSS, RBV and TM, MOMS-01, Metric Camera (MC) and Large Format Camera (LFC) images taken over test sites in the Khartoum/Gezira area; in the rugged and barren Red Sea Hills; and in the Kassala area close to the border with Ethiopia (Figure 1). Organisations that have carried out these tests have included the University of Glasgow (Petrie & El Niweiri, 1992, 1994), the University of Hannover (Engel & Konecny, 1985; Schroder, Schuhr & Schuring, 1985), Ordnance Survey International (OSI) (Hartley, 1987; Rackham, 1987); OEEPE (Rollin & Dowman, 1988); and the UN Economic Commission for Africa (Ihemadu, 1985). Also a test of simulated SPOT imagery for planimetric accuracy only was carried out at the University of Khartoum (Ali 1986). This concentration on the eastern part of Sudan for test sites was largely a consequence of the availability of all these different types of imagery over a cloud-free desert area. Allied to this was the availability of a substantial block of new 1:100,000 scale topographic mapping of the area produced from aerial photographs by DOS/OSI under a British aid programme. These maps were available for test and comparative purposes for these sites. While the Khartoum and Gezira areas contained many well defined points and objects, it was much more difficult to find such points in the Red Sea Hills test areas.

4.1 Tests of Monoscopic Scanner Imagery

With regard to the work carried out over these Sudanese test sites at the University of Glasgow in the late 1980s, a comprehensive series of tests of planimetric positional accuracy were first carried out over areas in the Red Sea Hills for four types of monoscopic scanner images - Landsat MSS, RBV and TM and MOMS-01 - having ground pixel values of 80, 30, 30 and 20 m respectively. The ground control points (GCPs) were taken from the then new 1:100,000 scale DOS/OSI maps, while the measurements of the GCP positions on the images were carried out on a Zeiss Jena Stecometer stereocomparator using stable film transparencies of these images. The Stecometer has a measuring resolution of 1 μm and an accuracy of ± 2 to 3 μm. Two-dimensional polynomial transformations were used to transform the image coordinates measured on the scanner images into terrain coordinates. For this purpose, approximately 40% of the ground control points were used as control points for the determination of the transformation parameters; the remainder were used as independent check points.

These transformed coordinate values were then compared with the values taken from the existing maps to produce the root mean square error (RMSE) values in easting (E), northing (N) and planimetry (Pl). A summary of the results are given in Table I; more detailed results are given in the paper by Petrie & El Niweiri (1992).

Table I - Results from the Planimetric Accuracy Tests of Scanner Imagery Conducted over the Red Sea Hills Area

	Control Points					Check Points			
Sensor	Pixel Size (m)	No.	m_E (m)	m_N (m)	m_{Pl} (m)	No.	m_E (m)	m_N (m)	m_{Pl}
MSS	80	50	±60	±52	±80	76	±57	±58	±81
TM	30	40	±31	±41	±52	58	±28	±40	±49
RBV	30	40	±28	±29	±40	47	±32	±26	±41
MOMS	20	20	±22	±20	±30	31	±18	±21	±28

Besides these planimetric accuracy tests, a series of interpretation tests were also carried out with the MSS, TM, RBV and MOMS-01 images. These were quite disappointing in terms of their possible contribution to the small scale topographic mapping of the Sudan. While the land forms, hydrology, forested and agricultural areas could be mapped with a reasonable certainty, the man-made infrastructure of towns, villages, communications and utility-related features (pipelines, power-lines, generating stations, etc.) were largely missing or incompletely recorded on the topographic maps that were derived from these various types of scanner image. Yet it is precisely these cultural features that the majority of map users (- though perhaps not geoscience users -) are most likely to want to be complete and up-to-date (Petrie & El Niweiri 1992).

4.2 Further Tests of MOMS-02 Scanner Imagery over a Sudanese Test Field

Recently, in 1996, further tests of MOMS-02 scanner imagery have been undertaken at the University of Glasgow using a test field in the Dindir area of Sudan located east of the Blue Nile River and north east of the Roseires Dam close to the border with Ethiopia. Unlike the previous monoscopic MOMS-01 imagery which was acquired using a vertical (nadir) pointing of its linear array sensor, MOMS-02 features along-track stereo-coverage (Fig. 2), acquired using forward and backward pointing linear array sensors with a 13.5m ground pixel size. With its 21.5° forward and backward viewing angles, this ensures the excellent base:height ratio of 0.8 for the stereo-imagery and offers good potential for height determination and the extraction of DEMs from these images. The images of the test area were acquired from a Space Shuttle mission in 1993 and have been used to carry out tests of the geometric accuracy and information content of MOMS-02 stereo-imagery. The radiometric quality of the image data was only moderate and required substantial pre-processing using the Adobe Photoshop package before it was really useable for the tests.

Figure 2: Geometry and stero-coverage of different types of stereo-space imagery

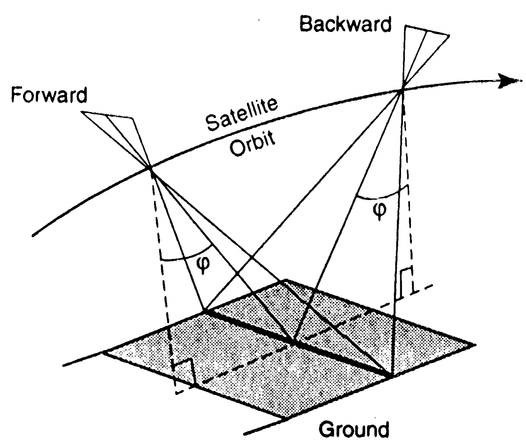

Figure 2'a) : Along track scanner imagery e.g. MOMS-02

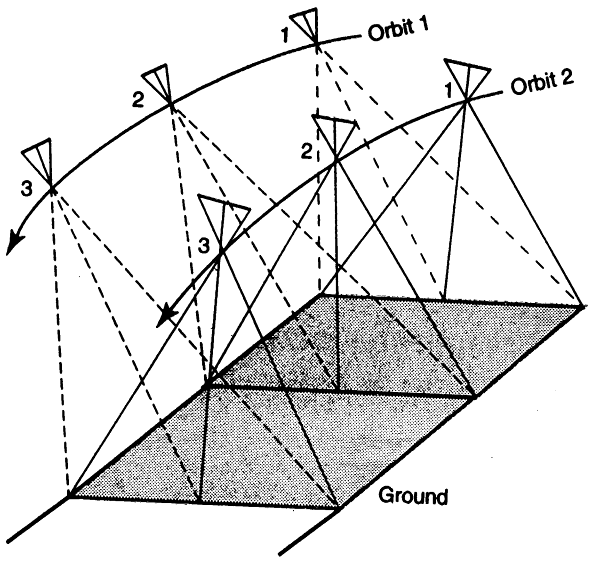

Figure 2-b) Cross-track scanner imagery
e.g. SPOT)

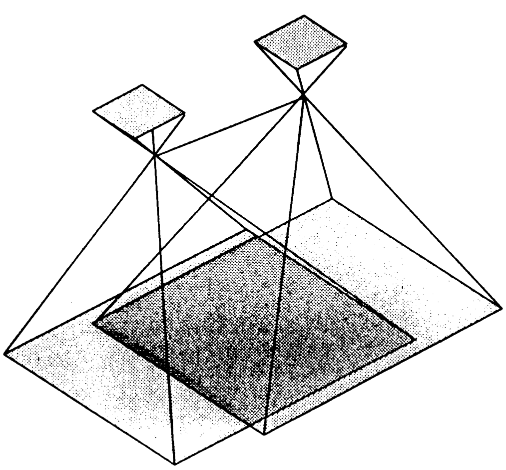

Figure 2© : Frame-type photographic camera imagery
e.g. MC and LFC

The modelling of the orbital path of the MOMS-02 sensor so that its position and attitude are known continuously throughout the time period during which the images have been acquired has been devised by one of the authors (MJV-Z). This is based on the use of the ephemeris data recorded on board the Space Shuttle to give the required information on the orbital parameters that have been used in the modelling. A bundle adjustment program based on this modelling and employing the classical collinearity equations of analytical photogrammetry has been written expressly for the purpose of carrying out the geometric accuracy test.

The Dindir test area which is covered by a single MOMS-02 stereo-pair (Scene 5 on Orbit 61) is very flat and is crossed by a number of meandering rivers. Parts of the area are covered by an agricultural development scheme with large fields based on irrigation but otherwise it is a semi-arid area with some scattered villages and cultivation. The ground control points (GCPs) used for the accuracy tests have been extracted from the DOS/OSI 1:100,000 scale maps covering the area using a precision scale with a least count of 0.1mm - equivalent to 10m at the map scale of 1:100,000. The image coordinate data for the GCPs was acquired through measurements made on a PCI EASI/PACE digital image processing system running on a Pentium-based PC. The geometric accuracy tests have been carried out for point determination in both 2-D (i.e. for planimetric position in terms of E, N coordinates on the UTM projection) and 3-D (in terms of X,Y,Z geocentric coordinates).

4.2.1 2-D Geometric Accuracy Tests of MOMS-02 Imagery

The results of the 2-D accuracy tests in terms of the RMSE values for the residual errors in ΔE, ΔN and ΔPl in metres at both the control points and the check points using a polynomial transformation and adjustment program are given in Table II below. Sets A to D refer to the different combinations of control and check points that have been utilised using the 49 available GCPs.

Table II - Results from the 2D (Planimetric) Accuracy Tests of MOMS-02 Scanner Imagery Conducted over the Dindir Test Field

		Control Points				Check Points			
Data Set	Pixel Size (m)	No.	m_E (m)	m_N (m)	m_{Pl} (m)	No. (m)	m_E (m)	m_N (m)	m_{Pl}
All Pts.	13.5	49	±14	±13	±20	-	-	-	
Set A	"	19	±14	±13	±19	30	±21	±19	±28
Set B	"	14	±14	±21	±26	35	±26	±20	±33
Set C	"	10	±6	±12	±13	39	±22	±23	±32
Set D	"	8	±12	±8	±14	41	±23	±21	±31

Having regard to the inherent accuracy of the 1:100,000 scale maps themselves and the accuracy with which the GCPs can be scaled from these maps, where 0.2 and 0.3mm are equivalent to 20 and 30 m respectively, these results can be regarded as being satisfactory.

4.2.2 3-D Geometric Accuracy Test of MOMS-02 Imagery

With regard to the tests of 3-D accuracy using the bundle adjustment program, the results in terms of the RMSE values for the residual errors in ΔX, ΔY and ΔZ in metres are given in Table III below.

Table III - Results from the 3D Accuracy Tests of MOMS-02 Stereo-Imagery Conducted over the Dindir Test Field

		Control Points				Check Points			
Data Set	Pixel Size	No.	m_X (m)	m_Y (m)	m_Z (m)	No. (m)	m_x (m)	m_Y (m)	m_Z
All Pts	13.5	49	±13	±19	±15	-	-	-	-
Set A	"	19	±13	±22	±17	30	±15	±21	±17
Set B	"	14	±10	±15	±12	35	±17	±29	±22
Set C	"	10	±9	±17	±6	39	±16	±25	±24
Set D	"	8	±11	±15	±7	41	±14	±26	±22

A parallel series of interpretation tests of the MOMS-02 imagery has also been carried out with similar results to those mentioned above for the MOMS-01 images - namely that there is a substantial shortfall in the features that can be extracted from the imagery, amounting to about 30% of the detail specified for inclusion in topographic maps at 1:100,000 scale.

4.3 2-D and 3-D Geometric Accuracy Tests of MOMS-02 Imagery over an Australian Test Field

Although the results given in Tables II and III can be regarded as satisfactory, it was obvious that their main limitations lay in the quality of the ground control points (GCPs) which had been derived from the 1:100,000 scale maps. In order to test out fully the geometric accuracy of the MOMS-02 imagery and to validate the modelling and the program developed at the University of Glasgow, it was necessary to find a more accurate test field. In fact, this became possible through the good offices of Dr. C. Fraser of the University of Melbourne, who, together with some colleagues, has established a very accurate test field of ground control points (GCPs) for an area in the south-east corner of the Northern Territory of Australia which had also been covered by a MOMS-02 stereo-pair (Fraser & Shao 1996). Like the Sudanese test field, this area is semi-arid in nature and exhibits little relief. The ground positions and heights of the GCPs were measured using Differential GPS techniques giving a nominal accuracy of less than 1 metre. A corresponding set of image coordinates which had been measured at the Department of Photogrammetry at ETH, Zürich by Baltsavias and Stallmann (1996) was also made available. This data was input and run in both the polynomial adjustment program and the MOMS-02 bundle adjustment program developed at the University of Glasgow to provide further (i.e. better) information on the geometric accuracies that can be achieved with MOMS-02 imagery.

The results of these additional tests given in terms of the RMSE values of the residual errors at the control points and check points in metres in different combinations (Sets A to D) are given in Tables IV and V below.

Table IV - Results from the 2D (Planimetric) Accuracy Tests of MOMS-02 Scanner Imagery Conducted over the Australian Test Field

		Control Points				Check Points			
Data Set	Pixel Size (m)	No.	m_E (m)	m_N (m)	m_{Pl} (m)	No.	m_E (m)	m_N (m)	m_{Pl} (m)
All Pts.	13.5	51	±7	±7	±10	-	-	-	
Set A	"	18	±5	±2	±6	33	±11	±12	±17
Set B	"	12	±6	±2	±7	39	±11	±11	±16
Set C	"	9	±5	±5	±7	42	±15	±12	±20
Set D	"	8	±2	±3	±4	43	±14	±13	±19

Table V - Results from the 3D Accuracy Tests of MOMS-02 Stereo-Imagery Conducted over the Australian Test Field

		Control Points				Check Points			
Data Set	Pixel Size (m)	No.	m_X (m)	m_Y (m)	m_Z (m)	No. (m)	m_X (m)	m_Y (m)	m_Z
All Pts	13.5	51	±5	±6	±7	-	-	-	-
Set A	"	18	±5	±5	±6	33	±5	±5	±7
Set B	"	12	±5	±6	±7	39	±6	±6	±8
Set C	"	9	±3	±6	±5	42	±8	±7	±8
Set D	"	8	±1	±6	±5	43	±7	±8	±8

As can be seen from a comparison of the two sets of tables for the Dindir results (Tables II and III) and the corresponding Australian results (Tables IV and V), there is a marked improvement in the RMSE values - more than two-fold in the case of the 3D test - when the more accurate ground control point data derived from Differential GPS measurements is used. These results are very promising, especially since the use of along-track stereo-imagery removes one of the major shortcomings of cross-track stereo-imagery (such as that produced by the SPOT and IRS-1C imagers) where the individual images making up the stereo-pair are acquired from different orbits, often several months apart. In such a situation, the appearance of a particular area or object on the two images of the stereo-pair may be quite different. For example, the appearance of the vegetation, cultivated areas and water bodies (rivers, lakes, marshes, etc.) will be very different both during and after the rainy season to that visible in the dry season. This causes problems with the formation and stereo-viewing of the stereo-model and may make the extraction of a DEM quite impossible either by manual observation or by automatic image matching. In fact, for this reason, virtually all the forthcoming Earth observation satellites designed to acquire stereo-imagery will adopt the along-track configuration, including SPOT-5, which is planned for launch in 2001.

4.4 3D Geometric Accuracy Test of MOMS-02 Imagery Over an Ethiopian Test Field

In the context of using satellite imagery for mapping in the Red Sea Region, it is also worth noting the 3D geometric accuracy test carried out by Lehner and Kornus (1995) on MOMS-02 data over an area near Lake Tana in Northern Ethiopia. The ground control point (GCP) data comprised 46 GPS points supplemented by aerial photographs and topographic maps at 1:50,000 scale. The RMSE values at the 34 check points used in the test were m_X = ±24m; m_Y = ±28m; and m_Z = ±13m. Obviously these results are unexpectedly poorer than might be expected using high quality control points fixed by GPS. Lehner and Kornus believe that this was due to the difficulties that they experienced in identifying the GCPs on the images, so the points were measured with a rather low accuracy.

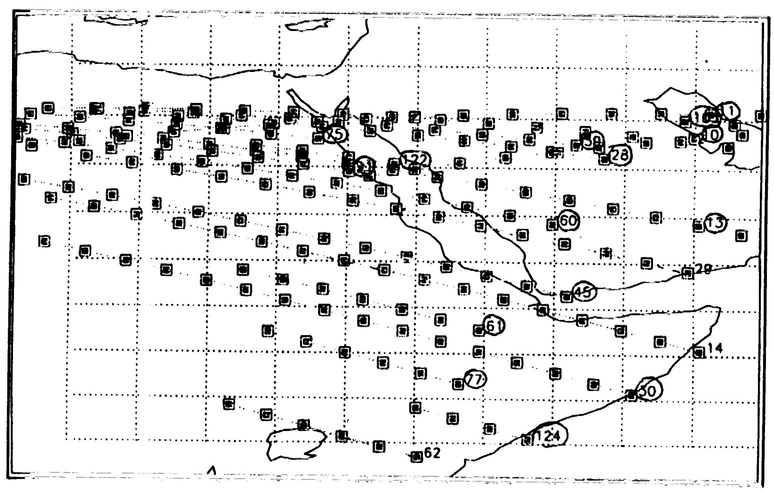

Figure 3 : MOMS-02 coverage of the Red Sea region

4.5 MOMS-02P Mission

The MOMS-02/D2 mission flown on-board the Space Shuttle in 1993 was purely an experimental one and was constrained in its coverage by the short duration of the mission and the low orbital inclination (i = 28.5°) of the platform. Thus it only produced fragmentary coverage between latitudes 28.5°N and S (Fig. 3). It is hoped to remove these constraints via a follow-on mission, for which the MOMS sensor has been refurbished and mounted in the PRIRODA module of the Russian MIR space station. Since this has an orbital inclination of 51° , if and when the MOMS-02P mission becomes fully operational, it will then be possible to acquire considerable coverage of the Earth between latitudes 51 °N and S during its planned 18 month mission. However, after some limited coverage had been acquired over the winter of 1996/97, the widely reported damage and difficulties with the MIR station encountered during the summer of 1997 have caused the MOMS-02 mission to be suspended; indeed if the damage is not fully repaired, the remaining part of the mission may not take place.

5. Tests of Stereo Space Photography in Sudan

In parallel with the original tests of the scanner images, a further series of tests were carried out at the University of Glasgow using stereo-pairs of space photographs. These were confined to the two main civilian space photographic systems operated by Western countries from the Space Shuttle - ESA's Metric Camera (MC) and NASA's Large Format Camera (LFC). Although attempts were made to obtain Russian space photography taken with the KFA-1000 camera for the same test areas in the Red Sea Hills, these were not successful. The main characteristics of the MC and LFC cameras and the resulting photography are set out below in Table VI.

Table VI - Characteristics of Space Shuttle Cameras and Photography

Camera	Format (cm)	Focal Length (m)	Angular Coverage	Flying Height (km)	Ground Coverage (km)	Scale	Ground Resolution (m)	B:Ht. Ratio	Orbital Inclination
MC	23x23	0.30	42x42°	250	190x190	1:820,000	16-23	0.3	28.5°
LFC	23x46	0.30	42x75°	225	170x340	1:740,000	10	0.6	57°

Accuracy tests using two stereo-pairs of each of these two types of spaceborne photography were carried out over test areas in the Red Sea Hills in Sudan. This region comprises a narrow coastal plain around 30 km wide, which is a desert, and then gives way to a wide belt of barren hills and mountains ranging in height up to 3,000 m above sea level. The MC coverage comprised photos nos. 110, 111 and 112 taken in December 1983 using false-colour film. The LFC photographs that were tested comprised exposures nos. 1319, 1320 and 1321 taken in October 1984 using very high resolution panchromatic film.

As with the tests of Landsat and MOMS scanner imagery, the plan and height coordinates of all of the ground control points (GCPs) were extracted from the 1:100,000 scale DOS/OSI maps. All of these GCPs were measured stereoscopically three times in the Stecometer and the mean of the three measurements was adopted as the image coordinates of each individual point. A preliminary program corrected the measured image coordinates for the effects of lens distortion and Earth curvature. The space resection/intersection analytical photogrammetric method was then used to generate the terrain coordinates for comparison with the known values of the ground control points obtained from the topographic maps. The results in terms of the RMSE values in metres of the residual errors in ΔE, ΔN (in UTM coordinates) and ΔH (in height) obtained at the control and check points in these accuracy tests are summarised as follows in Table VII.

Table VII - Results of the Accuracy Tests of MC and LFC Stereo-Space Photography over the Red Sea Hills Area

		Control Points					Check Points				
Camera	Scale	No.	m_E (m)	m_N (m)	m_{Pl} (m)	m_H (m)	No.	m_E (m)	m_N (m)	m_{Pl} (m)	m_H (m)
MC	1:950,000	30	±18	±18	±25	±30	40	±21	±21	±29	±32
LFC	1:750,000	30	±15	±12	±19	±19	55	±14	±13	±19	±18

Further interpretation tests carried out with these higher resolution MC and LFC images showed a very distinct improvement in interpretability as compared with that of the scanner imagery, though still the tracks and smaller sized settlements could not be detected reliably or with certainty. Obviously the location and the measurement of the substantial number of objects that were missing would entail a large effort and expense in terms of field completion. More details of these tests are given in the papers by Petrie and El Niweiri (1992, 1994).

5.1 Orthophotograph and DEM Extraction from Metric Camera Photography

The production of conventional small-scale topographic line maps is a costly and time consuming operation, especially when the various interpretation tests have shown that the topographic data derived from space imagery requires a great deal of field completion work on the ground to ensure that it meets standard topographic map specifications for content and accuracy. Thus much discussion has taken place over the years regarding their substitution by orthophotographs and orthoimage maps which, from the point of view of geoscience users, would ensure that the image details showing the geological, hydrological and other interesting morphological features were largely retained, while the geometry of the final product is that of a map. Almost always, this product will be accompanied by terrain elevation data in the form of a series of measured terrain profiles, a digital elevation model or contours derived from the measured height data - since the generation of this elevation data is a prior necessity for the production of an orthophotograph (from space photographs) or orthoimage (from space scanner imagery). Since little or no interpretation or feature extraction is involved, the method lends itself to the use of semi-automated or fully automated production methods and therefore to a considerable reduction in the time required to make the resulting products available to users.

Of course, there are well known drawbacks to generating and using image maps of this type - most notably that of shifting the burden of interpreting the orthophotograph or orthoimage and of completing the missing detail in the field from the map producers to the users. Nevertheless it is becoming an increasingly popular product, especially in arid areas where there is little or no cultural (i.e. man-made) detail such as roads and settlement. Thus the Sudan tests have included the generation of an orthophotograph and DEM, including a test of their accuracy and interpretability. This was carried out using the stereo-model formed by photos nos. 111 and 112 of the MC coverage.

The terrain elevation values were obtained for this stereo-model (covering an area of 180 x 180 km) through a dense series of parallel profiles measured in a Kern DSR analytical plotter. The absolute orientation of the stereo-model was carried out using 14 ground control points (GCPs), for which the RMSE values in easting, northing and height were ± 18 m, ± 18 m and ± 30 m respectively. The profiles were measured in a dynamic mode using a distance-controlled profiling routine with elevation values being measured every 400 m. 182,000 elevation points were measured in this way by a professional photogrammetrist along the 252 profiles required to cover the area of the model. These took a total of 40 hours to measure. The profile data were then input to the SCOP program installed at the Institute of Photogrammetry at the Technical University of Vienna to produce the denser grid-based DTM required for the production of the space orthophotograph. A computer controlled Wild OR-1 Avioplan analytical orthophotoprinter running under the SORA software package was then used in Vienna to produce the final orthophotograph at 1:250,000 scale. This scale was chosen since it lay just within the maximum enlargement ratio of 4:1 between the original photo (at 1:950,000 scale) and the orthophoto that can be accommodated by the OR-1 device.

5.1.1 2-D (Planimetric) Accuracy Test of the Space Orthophotograph

A planimetric accuracy test of the resulting orthophotograph was carried out using 75 of the ground control points (GCPs) that had been used in the preceding accuracy tests of the MC stereo-pairs. The corresponding points on the orthophotograph were measured using a large-format GTCO digitizer having a resolution (or least count) of 0.1 mm (100 μm). Thirty of the points were used as control points, the remaining 45 acting as independent check points. The results of this test in terms of the RMSE values for the residual errors in ΔE, ΔN and ΔPl in metres using both linear conformal and affine transformations are given in Table VIII.

Table VIII - Results of the 2D (Planimetric) Accuracy Test of the MC Orthophotograph of the Red Sea Hills Test Area

	Control Points (n=30)			Check Points (n=45)		
Transformation	m_E (m)	m_N (m)	m_{Pl} (m)	m_E (m)	m_N (m)	m_{Pl} (m)
Linear Conformal	±34	±34	±49	±28	±23	±36
Affine	±34	±34	±48	±31	±24	±39

The results which gave RMSE (mPl) values of ± 48 m in plan position at the control points and ± 38m at the check points can be regarded as extremely satisfactory, since they correspond to ± 0.2 mm and ± 0.15 mm respectively at the 1:250,000 scale of the final orthophotograph.

5.1.2 Accuracy Test of the DEM Data Extracted from the MC Space Photography

Using the PANACEA Digital Terrain Model (DTM) package (McCullagh 1988, 1990), the 182,000 measured elevation values were also used to generate a triangular-based DTM from which contours were derived at 20m intervals. A regular grid of elevation values at 200 m intervals was also interpolated and used as the basis for the construction of an isometric block diagram of the area using the PANORAMA module of the PANACEA package. The same grid-based elevation data set was also used to construct an alternative set of contours for the area. In addition, 1,300 elevation values were interpolated from the contour lines produced by DOS/OSI for the 1:100,000 scale topographic maps covering the test area. These were used as check points and compared with the corresponding elevation values given by the DTM produced from the MC space photography and extracted using the PANIC module of the PANACEA package. The resulting RMSE (m_h) values varied over the range of ± 16m for flat areas to

± 47m for different sub-areas within the test model area depending on the slope and complexity of the terrain.

A more detailed study of the accuracy of the elevation values obtained from the DEM was also undertaken for an area covering about half of the MC test stereo-model, which in turn covered three of the DOS/OSI 1:100,000 scale topographic map sheets (nos. 136, 163 and 164). This area was divided into 12 sub-areas (Fig. 4) according to their relief range and landform characteristics. Their main morphological characteristics are given in Table IX.

Sub-area A136 is a very flat piece of ground with slopes below 5° but, in the middle of the area, there is a quite small and isolated hilly area with slopes up to 40°. Sub-areas A163 and D36/B63 are also very flat areas with only a few isolated hills. However sub-areas B163, C163 and D163 are hilly with considerable height variations, while the area covered by sheet 164 is, in general, extremely mountainous with an elevation range from 650 m to 1,600 m and slopes up to 40°. This last area has been divided into four sub-areas, A to D164, with the former, the least hilly and the latter, the most mountainous and having steep slopes.

Table IX - Relief Parameters for the Red Sea Hills DTM Test Area

Area	Contour Range	Slope Range (°)	Typical Slope (°)
A136	540 m - 960 m	1 - 39	<5, 10
C136	530 m - 1,200 m	1 - 39	<5, 15
D136	620 m - 1,240 m	2 - 40	circa 16
D36/B63	550 m - 720 m	1 - 5	<5
A163	490 m - 600 m	1 - 15	<5
B163	550 m - 920 m	2 - 30	circa 10
C163	490 m - 920 m	1 - 30	circa 12
D163	530 m - 1,120 m	5 - 35	circa 20
A164	660 m - 1,040 m	1 - 30	circa 12
B164	720 m - 1,560 m	5 - 40	2 - 24
C164	650 m - 1,040 m	1 - 35	circa 15
D164	780 m - 1,360 m	5 - 40	circa 24

The results of this terrain analysis are given in Table X, where:-
+Emax and -Emin are the maximum positive and negative errors in elevation respectively;
RMSE is the root mean square error of the residual errors in elevation;
Mean is the average value of the residual errors;
SD is the standard deviation of the residual errors from the mean value; and
CP = Check Points.
N.B. The units used for the accuracy figures are all in metres.

Table X - Test Results for the DTM of the Red Sea Hills Test Area

Area	No. of CPs	+Emax	Emax	RMSE	Mean	SD
A136	82	19.5	-51.5	±16.1	-8.8	±13.5
C136	94	10.1	-68.1	±27.2	-23.0	±14.5
D136	129	68.5	-80.9	±25.1	-6.4	±24.3
D36/B63	117	24.9	-60.1	±25.9	-19.5	±17.0
A163	113	31.3	-47.2	±18.6	-6.6	±17.4
B163	126	69.1	-90.5	±29.9	-18.3	±23.7
C163	100	18.8	-72.8	±44.6	-41.7	±16.6
D163	165	42.5	-93.3	±42.0	-33.5	±25.3
A164	113	33.2	-72.1	±35.4	-30.8	±17.5
B164	105	60.7	-80.3	±38.2	-30.3	±23.4
C164	120	86.5	-75.6	±38.0	-32.1	±20.3
D164	125	92.7	-99.5	±52.2	-26.6	±37.2
Overall	1,389	92.7	-99.5	±34.1	-21.0	±26.8

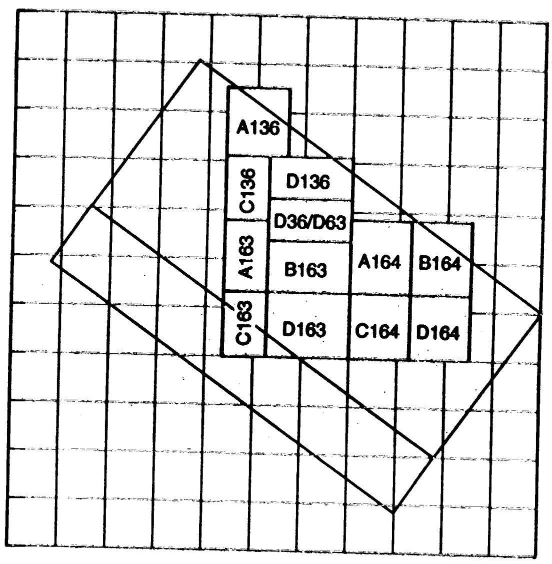

Figure 4: Sub-areas with different landform characteristics used in the accuracy test of the DEM extracted MC from stereo photography of the Red Sea Hills area

As can be seen from Table X, the elevation values extracted from the DTM produced from the MC stereo-pair tended to be too high as compared with those extracted from the DOS/OSI maps. Thus all the mean values of the residual errors had the same (negative) sign. In turn, this gave rise to substantial differences in the patterns of contours produced from the DTM as compared with those given by the DOS maps (Fig. 5). This affects the representation of both the terrain surface and its geomorphology by the DTM and contours produced from the MC space photography.

6. GEOMETRIC TESTING AND DEM GENERATION FROM STEREO-SPOT IMAGERY

While the geometric accuracy testing of MOMS-02 stereo-imagery that has been reported above in Section 4 is of much interest because of its relative novelty as an along-track stereo-imager, it must be said that, in recent years, SPOT has established itself as the prime sensor for the acquisition and supply of satellite imagery for small scale topographic mapping and map revision applications. For all its popularity, as evidenced by the mapping projects conducted by national mapping agencies mentioned in Section 3 of this paper, it still has certain shortcomings. In particular, these concern its limitations in terms of spatial resolution with a ground resolution of 15 to 18m derived from the 10m pixel size of its Pan images. This leads to a considerable shortfall in the extraction from the SPOT data of the communication networks and the finer cultural detail such as the smaller settlements required to be shown on topographic maps at 1:50,000 and 1:100,000 scales (Petrie & Liwa 1995). Furthermore, the accuracy of the heights and contours that can be derived from SPOT stereo-imagery may be regarded as being marginal or doubtful, especially given the specifications for a 10 or 20m contour interval often required for topographic maps at these scales.

However, many in the geophysical and geoscience communities have a strong interest in the DEMs and the orthoimages that can be derived from SPOT satellite imagery both as a substitute for topographic maps that may be difficult to acquire and as a base for field mapping. Also these products can be used for regional geophysical work and for the monitoring of the changes in coastal, desert and volcanic land forms within the Region that take place over a period of time. In particular, with the advent of digital photogrammetric systems - especially those from the established suppliers of image processing systems for use with remotely sensed imagery, such as Erdas (OrthoMAX), PCI (EASI/PACE), MicroImages (TNT-mips) and R-WEL (DMS) - geoscience users now have more ready access to systems featuring automatic image matching from SPOT stereo-pairs for the production of DEMs and orthoimages. However, till now, there have been very few independent studies to assess the quality of the elevation data generated by such automated systems (Trinder *et al* 1994). In this respect, it will have been noted that almost all of the topographic mapping carried out by national mapping agencies from satellite imagery within the Region has involved the use of analytical plotters using hard copy (film) images and manual (operator-controlled) measurements of heights, profiles and contours.

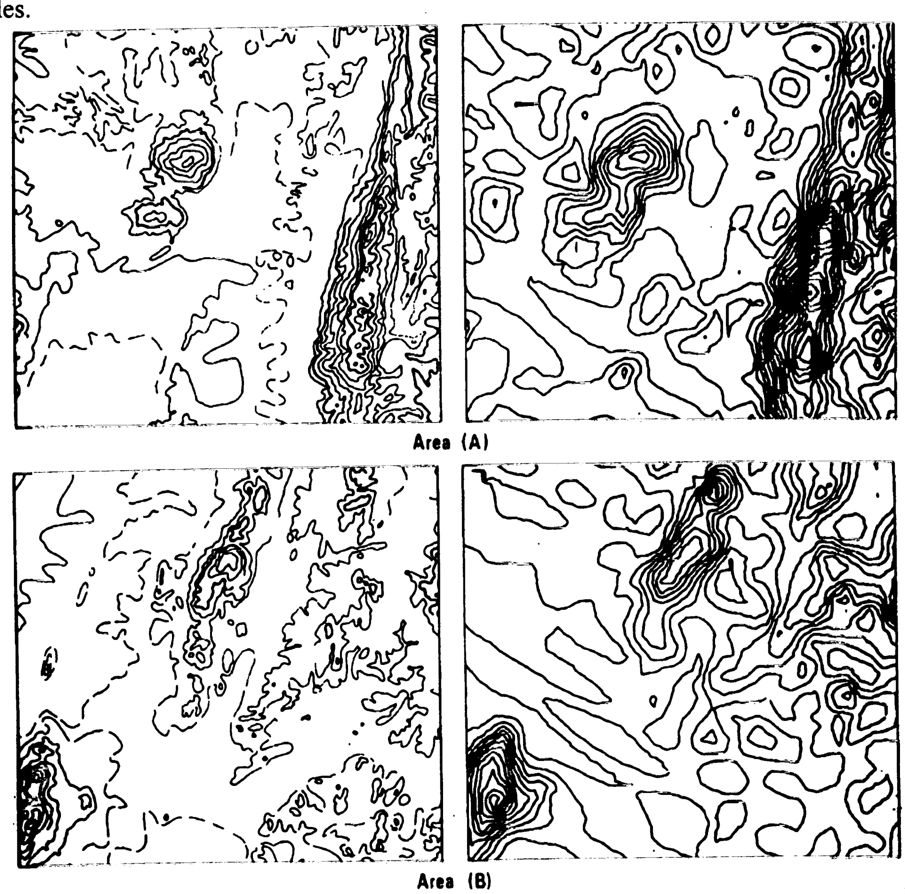

Figure 5: Comparison of contours contained on parts of the existing 1:100,000 scale DOS/OSI topographic maps of the Red Sea Hills area (left) and those derived from the DEM extracted from MC stereo-space photography (right) for two representative areas.

6.1 Project and Test Area

Research work into the calibration of these new systems and the validation of the DEMs and orthoimages generated by them is currently under way at the University of Glasgow as part of a major inter-disciplinary scientific study of part of the Badia area of North Eastern Jordan. This study is being carried out by a large group of British and Jordanian scientists under the joint aegis of the Royal Geographical Society (RGS) in London and the Higher Council for Science & Technology (HCST) in Amman. The production of a DEM and an orthoimage mosaic for the whole of the large area covered by the Project is intended to form part of the topographic data base for the Geographic Information System (GIS) being set up for the Badia Project. More specifically, the DEM will be of particular use and interest to those geoscientists who are studying the geology, geomorphology, soils and hydrology of the area.

The study area covered by the Badia Project is mostly a stony desert with an old lava flow occupying a substantial part of it. Much of the surface of the lava is covered in boulders and is extremely difficult to cross either on foot or in vehicles. There is some scattered agriculture with fields, small villages, etc. located in the north-west corner of the study area. The ground slopes in a fairly regular manner from north-west to south-east diagonally across the area with a few intervening hills and ridges and a number of dry stream channels (called wadis) which fill up with water for short periods during the occasional rainstorms and drain into the interior basin of Al-Azraq with its fluctuating lake levels and salt pans. The highest point in the study area lies in its north west corner on the southern flank of a mountain (a former volcano) called Jebel Al-Arab whose summit is located just across the border in Syria and has an elevation of about 2,000m. The lowest point is located in the southern edge of the area bordering Saudi Arabia and has an elevation value of around 500m. So there is an elevation difference of 1,500m across the area covered by the SPOT stereo-models.

6.2 Test Material and Data

The test material consists of a block of five SPOT Pan Level 1B stereo-pairs with a 10m pixel size covering the whole of the Badia Project area, comprising scenes 122/285; 123/285; 123/286; 124/285; and 124/286. Also a Level 1A stereo-pair has been acquired for comparative purposes for scene 122/285 which has been used intensively as the main test or reference stereo-pair. These scenes are all of a good image quality, being free from the dust and haze which spoils many of the satellite images of the Red Sea Region. Also the individual images comprising each stereo-pair have been taken with only a small time gap (one to three months) between them, so, over this desert area, there are no difficulties arising from changes in the appearance of the vegetation, cultivated areas and water bodies which might cause problems in forming and viewing the stereo-models and in extracting elevation information from them. Furthermore all of these SPOT stereo-pairs have an excellent base-height ratio (0.86 to 0.98) which promises good elevation accuracies, especially when the area is so largely devoid of vegetation that might interfere with the heighting process.

The Royal Jordanian Geographic Centre (RJGC) - which is Jordan's national mapping agency - has established the ground control points (GCPs) for the five stereo-pairs by Differential GPS methods carried out using five of the latest Ashtech dual frequency geodetic quality sets. The planimetric and height accuracies in terms of the RMSE values for each of the GCPs are better than ±1 metre. Altogether 130 GCPs have been established over the whole area. 60 of these points are located in the main test stereo-model (122/285).The remaining 70 points are scattered fairly evenly across the remaining four stereo-models so that there are 15 to 20 GCPs in each of these models.

The position of each GCP was marked on an enlargement of the SPOT image in the field and a supplementary diagram was constructed on the spot by the field surveyors. After processing the GPS data, the RJGC produced a coordinate list which gives the coordinate values of the GCPs in different systems:-

I. WGS84 geocentric coordinates;
II. Geographical (latitude/longitude) values;
III. Universal Transverse Mercator (UTM) values; and
IV. Jordan Transverse Mercator (JTM) values -the local or national system used in Jordan.

6.3 Problems and Solutions with Level 1B Stereo-Pairs

When the tests of the different systems (EASI/PACE, DMS, OrthoMAX, etc.) commenced, various difficulties were encountered with all of them; each system gave rise to a quite different set of problems. This resulted in a very intensive and highly interactive collaboration with the respective system suppliers (PCI, R-WEL, Erdas, etc.) to locate the sources of these problems and to produce solutions for them. In this respect, it should be noted that each of the different systems uses a quite different photogrammetric solution and quite different image matching algorithms for the generation of the DEMs.

However one commonly encountered problem concerned the use of SPOT Level 1B imagery. This is used quite widely by the geoscience community since its geometry is approximately orthographic and therefore more "map like" as a result of the preliminary processing which corrects for the tilt angle, Earth rotation, etc. - though it still contains the displacements due to terrain relief - thus allowing it to be used for the extraction of DEM data. In one or two cases, the package did not take account of the fact that the processing of the Level 1B images carried out by the SPOT Image processing facility in France had changed - a third order polynomial had been used up till the autumn of 1995, while a fifth order polynomial had been used after that. However this particular problem was not encountered with the DMS package which was designed from the outset to handle SPOT Level 1B images only

Various different solutions to these problems have been developed independently both at the University of Glasgow and by the suppliers concerned. In the case of the Level 1B problem, in each case, the procedure that has been adopted has been to convert the Level 1B image back to its Level 1A form. In the case of PCI EASI/PACE, this has been done by reading the polynomial coefficients which had been used to produce the Level 1B images and which appear in the header of the image data. Once these have been read, a reverse transformation is carried out to create the equivalent Level 1A data. In the case of the Glasgow solution (devised by MJV-Z) a two-step procedure is employed, by first transforming the rhomboidal shape of the Level 1B image to a rectangular image. This will still have too large a size compared with the square shape and dimensions of the equivalent Level 1A image, so a second transformation is applied to achieve this result. Additional corrections are then applied within the bundle adjustment program to ensure that a correct modelling of the attitude parameters is achieved to give a good orientation of the stereo-model and to ensure its fit to the GCPs (Valadan Zoej and Petrie 1998). The modified bundle adjustment program that implements this solution at the University of Glasgow has been written in the C++ programming language and runs on a 486-based PC.

6.3.1 Results Using the University of Glasgow Solution

The five Level 1B stereo-pairs covering the Badia Project area have each been tested using the University of Glasgow program. The test utilised 38 GCPs, which were divided into two groups in various different combinations (or Sets). The first group in each Set were used purely as control points for the determination of the parameters of the analytical photogrammetric solution. The second group were used solely as independent control points. The residual errors at the control points and check points for the main test model,122/285, are given below in Table XIII as RMSE values for ΔX, ΔY and ΔZ in metres at both the control points and the check points.

Table XI - Results of Accuracy Tests in Position and Height of the Main SPOT Level 1B Stereo-Pair (122/285) over the Badia Test Field Using the University of Glasgow Solution

		Control Points				Check Points			
Data Set	Pixel Size (m)	No.	m_X (m)	m_Y (m)	m_Z (m)	No.	m_X (m)	m_Y (m)	m_Z (m)
All Pts	10	38	±7	±7	±8	-	-	-	-
Set A	"	15	±5	±5	±6	23	±9	±8	±10
Set B	"	10	±4	±3	±10	28	±9	±8	±7
Set C	"	8	±2	±3	±6	30	±9	±9	±10
Set D	"	6	±3	±3	±3	32	±9	±8	±12

Vector plots show that the residual errors at the individual control and check points are random both in extent and direction. This confirms that the solution developed by MJV-Z is a practical way of overcoming the problems encountered in the processing of the Level 1B imagery of the Badia area.

6.3.2 Results Using the PCI EASI/PACE Solution

The modified solution developed quite independently for EASI/PACE by PCI is now giving similar accuracies. For the main test model, 122/285, the RMSE values for the residual errors in ΔE, ΔN and ΔH in metres are summarized in Table XIV for different combinations (Sets A, B and C) of control and check points.

Table XII - Results of Accuracy Tests in Position and Height of the Main SPOT Level 1B Stereo-Pair (122/285) over the Badia Test Field Using the PCI EASI/PACE Solution

		Control Points				Check Points			
Data Set	Pixel Size (m)	No.	m_X (m)	m_Y (m)	m_Z (m)	No.	m_X (m)	m_Y (m)	m_Z (m)
All Pts	10	48	±5	±5	±7	-	-	-	
Set A	"	33	±4	±5	±5	15	±7	±5	±5
Set B	"	23	±5	±5	±4	25	±5	±6	±6
Set C	"	13	±3	±4	±3	35	±6	±6	±6

A much more detailed report of the results of testing the PCI EASI/PACE package over the Badia test field is given in the paper published by Al-Rousan et al (1997).

6.3.3 Results Using the R-WEL DMS Solution

It should be noted that the SPOT module in the DMS package does not utilize the full 3D spatial solution based on collinearity equations that is employed in all the other systems tested. Instead it utilizes a unique approach based on a 2D polynomial transformation to carry out the initial planimetric rectification, followed by automatic image correlation to produce the height parallaxes from which the elevation values are derived.

The results from tests carried out using the R-WEL DMS package over the main test model (122/285) are given in Table XIV which again gives the RMSE values of the residual errors in ΔE, ΔN, ΔPl and ΔH in metres for different combinations (Sets A, B and C) of control and check points.

Table XIII - Results in Accuracy Tests in Position and Height of the Main SPOT Level 1B Stereo-Pair (122/285) over the Badia Test Field Using the R-WEL DMS Solution

		Control Points				Check Points			
Data Set	Pixel Size (m)	No.	m_X (m)	m_Y (m)	m_Z (m)	No.	m_X (m)	m_Y (m)	m_Z (m)
All Pts	10	45	±9	±9	±7		-	-	-
Set A	"	35	±9	±8	±5	10	±6	±7	±7
Set B	"	25	±9	±8	±4	20	±10	±7	±7
Set C	"	15	±9	±8	±6	30	±9	±8	±6
Set D	"	10	±8	±8	±6	35	±11	±9	±5

The work done till now shows clearly the value of having an excellent test field such as that created by the RJGC for the Badia Project area to allow the calibration of systems and tests of geometric accuracy to be carried out. At the present time, work is continuing on the testing of the OrthoMAX and TNT-mips packages

7. DEM Extraction

With regard to the automatic extraction of the elevation values for each of the Level 1B stereo-pairs using image Badia Project area with only a few gaps or holes matching, this has been carried out using the appropriate module from the EASI/PACE and DMS packages. In general terms, these modules have worked well with all five Level 1B stereo-pairs. In spite of the almost complete lack of cultural detail in this desert area, the matching algorithms used with each of the packages have worked extremely reliably and has produced elevation values for 98% of the where correlation has failed, e.g. in shadow areas lacking texture.

The EASI/PACE software also provides facilities to merge the individual DEMs derived from each stereo-pair into a single seamless elevation model. Again, in the case of the Badia area, no difficulties were encountered with this merging operation. There were no abrupt changes in the elevation values in the overlap areas between the stereo-pairs and a smooth transition is apparent. The data volumes generated by the final merged DEM are of course very large. In the case of the data generated by the five SPOT stereo-pairs covering the Badia area, using 16-bit data, the merged data set amounts to 534 Mbytes when a 20m interval (=2 pixels) between the matched points is used. The final merged DEM covers an area roughly 90 x 120km in size.

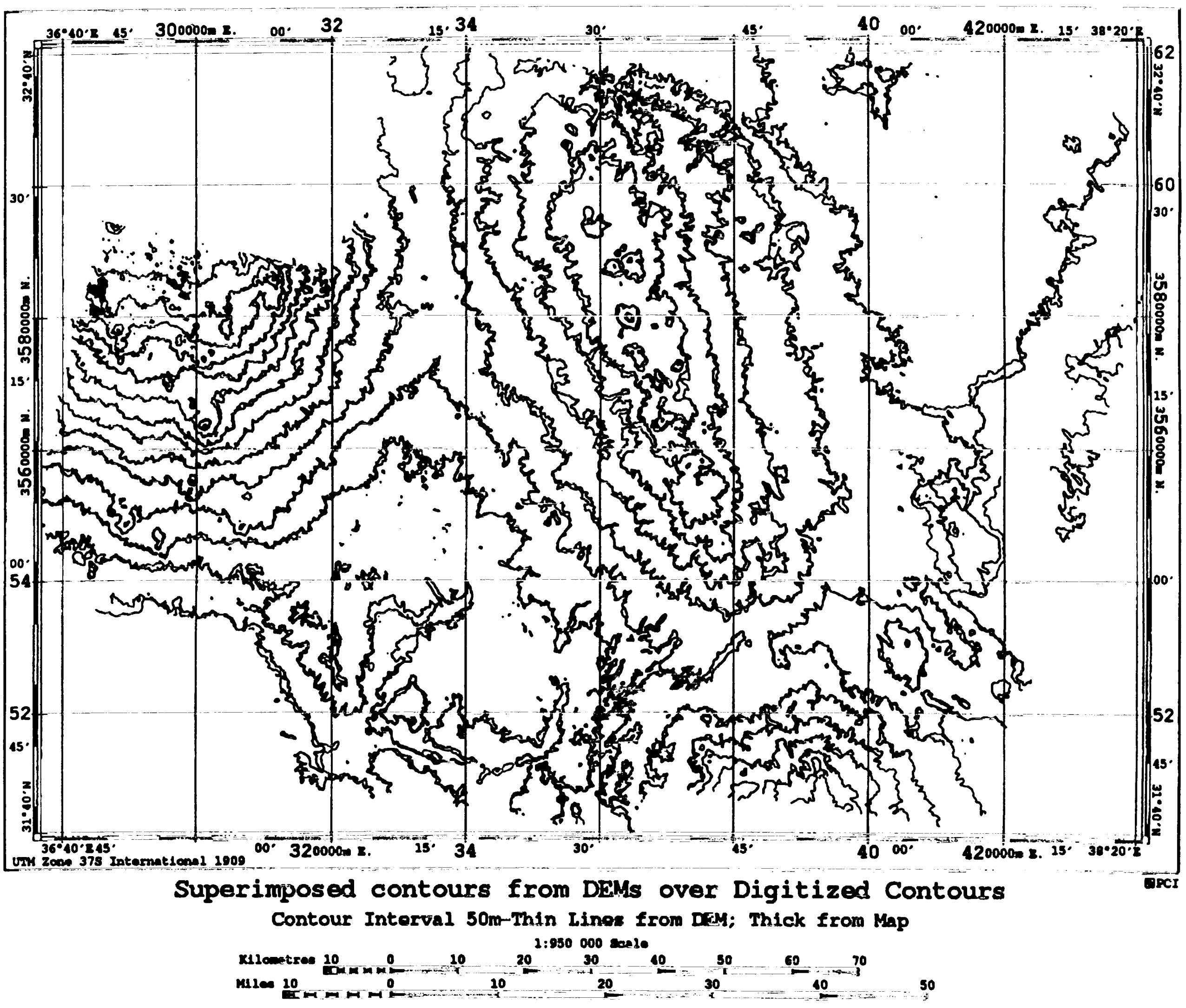

Figure 6: Contours at 50m interval derived from the DEM of the Badia area, Jordan extracted from five SPOT Level 1B stereo-pairs. These have been superimposed on the contours digitized from the existing 1;250,000 scale topographic map of the area.

In the case of the EASI/PACE package, contours may also be derived from the DEM data using a module provided for the purpose. However with DMS, one needs to use software from a third party supplier such as the SURFER package to generate the contours. A preliminary validation check superimposing the contour lines from the merged DEM of the Badia area over the contours at a 50 interval derived from the 1:250,000 scale topographic map of the area shows an excellent agreement between the two (Fig. 6) for EASI/PACE. With DMS, most of the area is well represented, but in a few areas, the match is somewhat less good. Detailed accuracy testing of the DEM data and the contours produced from this data against the contours of the existing topographic map of the area produced photogrammetrically from aerial photography shows RMSE values of ± 6 to 8m in elevation. Besides the contour plots, various other products can be derived from the DEM by the EASI/PACE package, including "fishnet-type" perspective block diagrams. An example is included as Fig. 7. Further work on the validation of the DEM of the Badia Project area using elevation profiles measured by kinematic GPS techniques across the area is now under way.

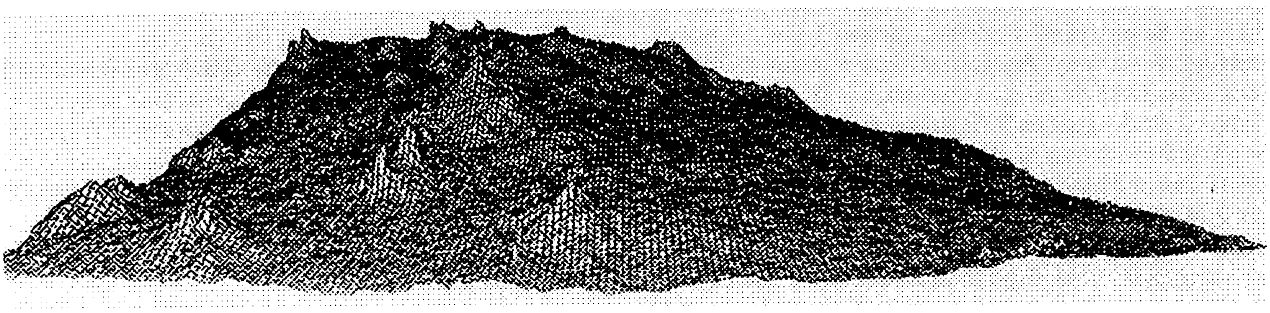

Figure 7: Perspective block diagram of part of the Badia area constructed from the DEM produced from SPOT stereo-pairs

8. ORTHOIMAGE GENERATION

The DEM data set also forms part of the base data required for the orthorectification process. First an orthoimage has been generated from each individual Level 1B stereo-pair; later these have all been merged together using the facilities provided by the appropriate EASI/PACE and DMS modules to form a single seamless orthoimage mosaic amounting to 56 Mbytes of data using a pixel size of 20m. Once again, the merging operation went smoothly and there are no obvious joins visible between the individual component images. In this respect, the images had all been taken within a quite a short time period, two to three months apart. Furthermore this desert area lacks the seasonal changes in vegetation which might give difficulties elsewhere when the stereo-pairs were acquired at different times in the growing cycle. Fig. 8 shows the overall mosaic of the Badia Project area - the extent of the large lava flow which covers so much of the surface of this area can be seen quite clearly.

Regarding the geometric accuracy of the final orthoimage, a check was carried out by measuring quite independently on the orthoimage the positions of 43 of the GCPs lying within the area of the main test scene, 122/285. Using a simple linear conformal (first-order) transformation, the measured image coordinates were then transformed into their equivalent UTM terrain coordinates. These were then compared with the corresponding coordinate values derived from the GPS ground survey. The resulting RMSE values of the residual errors in ΔE and ΔN were ±9m, which, for the 20m pixel size used to produce the final orthoimage, gives RMSE values of ±0.45 pixel in both the x and y directions on the ortho-image. The vector plot of the individual residual errors resulting from this comparison showed a completely random distribution with no systematic components. This confirmed the excellent results of the whole process in geometric terms as well as in qualitative terms.

9. DISCUSSION AND CONCLUSION

The standard specifications for topographic mapping at the 1:50,000, 1:100,000 and 1:250,000 scales used by most geoscientists are set out in Table XIV.

Table XIV -Topographic Map Specifications

Scale	Plan Resolution (at 0.1mm)	Plan Accuracy (±0.3mm)	Spot Height Accuracy (m)	Contour Interval (m)
1:50,000	5 m	± 15 m	± 3 m	10 to 20 m
1:100,000	10 m	± 30 m	± 6 m	20 m +
1;250,000	25 m	± 75 m	± 15 m	40 to 50 m

From this table, it can be seen that for the 1:50,000, 1:100,000 and 1:250,000 scales, the required planimetric accuracies (for mPl = ±0.3 mm) are ±15 m, ±30 m and ±75 m respectively.

From the results of the extensive series of tests given above, it can be seen that, in terms of the planimetric accuracy of the topographic maps and orthoimages derived from stereo space images, there is no difficulty in meeting the specifications for these scales. However the shortfall in the information content and the features that can be extracted from the various types of space imagery available at the present time remains the main hindrance to the more extensive use of such imagery for mapping in the region. This arises from the limitations in ground resolution of the imagery. - for example, the SPOT Pan and MOMS-02 scanner imagery have ground pixel sizes of 10 m and 13.5 m respectively, which translate to ground resolutions of 15 to 20 m and 18 to 25 m respectively. These values fall far short of the resolution values - 2 to 5 m - needed to extract the smaller communication and settlement features present in the region which need to be included in maps at these designated scales. This leads to needs for extensive and expensive field completion to supplement the information derived from the space imagery.

With regard to elevation accuracies, those achievable from stereo space imagery are marginal in terms of satisfying the specifications for mapping at 1:50,000 scale where contour intervals of 10 m and 20 m are typical. The spot height accuracies of ±7 to 10 m achieved at independent check points in the tests carried out with SPOT and MOMS-02 stereo-pairs (- provided accurate GPS control points are available -) translate to contour intervals of 25 to 30 m. Thus there may some doubt about using these images to satisfy the standard map specifications for contouring at that scale. If however a more relaxed specification is acceptable to geoscience users, then the elevation data derived from stereo space imagery could be very useful. At 1:100,000 and 1:250,000 scales, the map requirements are often for contours at 40 or 50 m, in which case, the satellite images should be quite capable of supplying the required contour and elevation data, provided that the photogrammetric operations are based on the availability of good quality ground control points.

Acknowledgements

Over the years, a great deal of assistance has been given by OSI in the provision of maps and other data to enable the various tests to be carried out over the Sudanese test sites; in particular, the help given by Mr. R. Fox is gratefully acknowledged. It is a pleasure also to acknowledge the valuable help given by Dr. C. Fraser and Dr. E Baltsavias through the provision of the GCP and measured image coordinate data to allow the MOMS-02 imagery to be tested over the Australian test field. Furthermore much valuable technical assistance and advice regarding the characteristics of the MOMS-02 imagery has been given by Dr. W. Kornus and Mr. M. Lehner of DLR. In addition, Brigadier Salim Khalifa, the Director of the RJGC, must be thanked for his excellent cooperation with regard to the setting up of the Badia test field, while still further thanks must be given to the several members of his field survey staff who have carried out the fixing of the ground control points and the creation of the test field in the difficult terrain of the area in such an admirable and professional manner. Furthermore the considerable assistance given by Dr. P. Cheng of PCI and Dr. Th. Toutin of CCRS in Canada in helping to solve the difficulties posed by the SPOT Level 1B stereo-pairs is acknowledged with grateful thanks, as is the cooperation of Professor R. Welch and Mr. T. Jordan of R-WEL in modifying the DMS software in the light of the results of the tests carried out over the Badia area. Finally sincere thanks are due to Mr. M. Shand for his production of the diagrams included in this paper.

REFERENCES

Ali, A.E., 1986 - An Experiment on the Investigation of SPOT Imagery for Topographic Mapping in Sudan. Proceedings of the Twentieth International Symposium on Remote Sensing of the Environment, Nairobi, Kenya: 1403-1409.

Al-Rousan, N., Cheng, P., Petrie, G., Toutin, Th. and Valadan Zoej, M.J., 1997 - Automated DEM Extraction and Orthoimage Generation from SPOT Level 1B Imagery. Photogrammetric Engineering & Remote Sensing, 63 (8): 965-974.

Baltsavias, E.P. and Stallmann, D., 1996 - Geometric Potential of MOMS-02/D2 Data for Point Positioning, DTM and Orthoimage Generation. International Archives of Photogrammetry & Remote Sensing, 31 (B4): 110-116.

Engel, H. and Konecny, G., 1985 - Orthophotomapping from Metric Camera Imagery. Proceedings, Metric Camera Workshop (DFVLR-ESA), Oberpfaffenhofen: 13-18.

Fraser, C.S. and Shao, J., 1996 - Exterior Orientation Determination of MOMS-02 Three-Line Imagery: Experiment with the Australian Testfield Data. International Archives of Photogrammetry & Remote Sensing, 31 (B3): 207-214.

Hartley, W.S., 1987 - Map Compilation and Revision in Developing Countries: Test of Large Format Camera Photography, STS-419. Proceedings, ISPRS Colloquium on Use of Space Photographic Data for Mapping, Leipzig: 144-147.

Ihemadu, S., 1985 - Satellite Remote Sensing as a Mapping Tool. ITC Journal, 1985-3: 187-191

Jobre, N., 1993 - EMA's Experience with the Production of 1:50,000 Photomaps using SPOT Images and GPS Survey. Presented Paper, Eighth UN Regional Cartographic Conference for Africa, Addis Ababa. 5pp.

Lehner, M. and Kornus, W., 1995 - The Photogrammetric Evaluation of MOMS-02 Mode 3 Data (Mexico, Ethiopia). Proceedings of the International Workshop on International Mapping from Space, Madras, India: 51-68.

McCullagh, M.J., 1988 - Terrain and Surface Modelling: Theory and Practice. Photogrammetric Record, 12 (72): 747-779.

McCullagh, M.J., 1990 - Digital Terrain Modelling and Vizualization: Chapter 9 in Terrain Modelling in Surveying & Civil Engineering (Eds. G. Petrie & T.J.M. Kennie): 128-157.

Medhin, H.G., 1993 - Mapping in Ethiopia. Spot Magazine, 20: 18-19.

Medhin, H.G., 1995/1996 - Ethiopian Mapping Authority (EMA) - Looking into the Future. Presented Paper, Cambridge Conference of National Mapping Organisations (1995) and National Report, XVIII ISPRS Congress, Vienna (1996): 5pp.

Murray, K.J. and Gilbert, E.V., 1990 - Small Scale Line Mapping from SPOT Imagery by Ordnance Survey of Great Britain. Proceedings of the Twenty Third International Symposium on Remote Sensing of Environment, Bangkok, Thailand: 1149-1158.

Murray, K.J. and Newby, P.R.T., 1990 - Mapping from SPOT Imagery at the Ordnance Survey International Archives of Photogrammetry & Remote Sensing, 28(4): 430-438.

Petrie, G. and El Niweiri, A.E.H., 1992 - The Applicability of Space Imagery to the Small Scale Topographic Mapping of Developing Countries: A Case Study - the Sudan. ISPRS Journal of Photogrammetry and Remote Sensing, 47(1): 1-42.

Petrie, G. and El Niweiri, A.E.H., 1994 - Comparative Testing of Space Imagery for Small-Scale Topographic Mapping of Sudan. ITC Journal, 1994-2: 95-112.

Petrie, G. and Liwa, E.J., 1995, - Comparative Tests of Small-Scale Aerial Photographs and SPOT Satellite Images for Topographic Mapping and Map Revision in Eastern, Central and Southern Africa. ITC Journal, 1995-1: 43-55.

Petrie, G., 1997 - The Current Situation in Africa Concerning Topographic Mapping and Map Revision from Satellite Images. ITC Journal, 1997-1: 49-63.

Rackham, L., 1987 - An Evaluation of Spacelab Metric Camera Imagery of Sudan. Survey Review, 29 (224): 5-62.

Rollin, J. and Dowman, I.J., 1988 - Map Compilation and Revision in Developing Areas: Test of Large Format Camera Imagery. OEEPE Publication, 22: 35pp.

Schroeder, M., Schuhr, W. and Schuring, A., 1985 - Line Mapping and Resolution Tests with Metric Camera Data. Proceedings, Metric Camera Workshop (DFVLR-ESA), Oberpfaffenhofen, 87-90.

Trinder, J.C., Vuillemin, A., Donnelly, B.E. and Shettigara, V.K., 1994 - A Study of Procedures and Tests on DEM Software for SPOT Images. International Archives of Photogrammetry & Remote Sensing. 30 (4): 449-456.

Valadan Zoej, M.J. and Petrie, G., 1998 - Mathematical Modelling and Accuracy Testing of SPOT Level 1B Stereo-Pairs. To be published in Photogrammetric Record, 15 (91).

Veillet, I., 1990 - Block Adjustment of SPOT Images for Large Area Topographic Mapping. Presented Paper, ISPRS Commission IV Symposium, Tsukuba, Japan, 10pp.

Veillet, I., 1992 - Accuracy of SPOT Triangulation with Very Few or No Ground Control Points. International Archives of Photogrammetry & Remote Sensing, 29 (B4): 448-450.