Automated DEM Extraction and Orthoimage Generation from SPOT Level 1B Imagery

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Abstract
This paper describes the testing and validation of the photogrammetric modules of the PCI EAS/PACE system using SPOT stereo-pairs over a high accuracy test field established in a desert area in Jordan. The mathematical modeling and analytical photogrammetric solution used by the system are first described. This is followed by a description of the algorithm employed in the automatic image matching procedure used to extract a dense DEM from the SPOT digital image data. The results of extensive tests of the geometric accuracy of the exterior orientation and analytical rectification carried out with the SPOT images using EAS/PACE are given. The DEMs generated from five SPOT Level 1B stereo-pairs have been merged and validated through a comparison of the resulting contours with the corresponding contours generated by aerial photogrammetric methods, the two plots showing an excellent agreement. The final ortho-images are of a high quality in radiometric terms, while a check of their geometric accuracy reveals sub-pixel accuracy. The results of this highly automated all-digital photogrammetric procedure are of considerable relevance to those concerned with the topographic mapping of extensive areas of arid and semi-arid terrain.

Introduction — The Use of SPOT Stereo Imagery for Topographic Mapping
Up until now, topographic mapping from satellite stereo imagery has been based mainly on the use of SPOT Pan imagery with its 10-m pixel size produced from an orbital altitude of 820 km with a 60-km swath width and with overlapping cross-track coverage giving base:height ratios of up to 1.0. This mapping work has been carried out largely using analytical plotters in conjunction with hardcopy film transparencies and manual, operator-controlled measurements resulting in the production of classical vector line maps. For example, in the countries of the Red Sea region, which are of particular concern to the three of the authors from the University of Glasgow, the mapping of northeast Yemen at 1:100,000 scale with a 40-m contour interval has been carried out in the late 1980s under a British aid program by Ordnance Survey International (OSI) from 18 SPOT Pan stereo models (Murray and Newby, 1990; Murray and Gilbert, 1990). These maps were compiled and plotted in a Korn DSR analytical plotter supplemented by a thorough field completion of the villages, buildings, minor roads, and tracks which could not be plotted due to the shortfall in ground resolution of the SPOT imagery. At much the same time, the French Institut Geographique National (IGN) has carried out the mapping of the whole of the territory of Djibouti at 1:200,000 scale from 16 SPOT Pan stereo-pairs with the more developed part being covered at 1:50,000 scale (Veillet, 1990; Veillet, 1992). The actual stereo compilation was carried out on Matra analytical plotters, again supplemented by a comprehensive field completion to produce the traditional type of line map. In addition to these examples of original mapping, SPOT stereo-pairs have also been used in Saudi Arabia for the revision of the 1:250,000-scale Joint Operations Graphics (JOG) used mainly for air navigation. This has been carried out by the Saudi Military Survey Department (MSD) for the sensitive border areas with Yemen, Oman, Iraq, Jordan, etc., where “no-fly” zones operate and the use of aerial photography is not practicable. Again, this has been carried out using Intergraph IMD digital stereo-plotters based on the company’s Image Station have also come into use for this task.

Recently in Ethiopia (Jobre, 1993; Medhin, 1993), the Ethiopian Mapping Agency (EMA) has used SPOT Pan stereo-imagery for the continuation of its program of basic mapping of the country at 1:50,000 scale. Again, this uses hardcopy images on an analytical plotter, in this case, a Wild BC2 instrument running the Aviosoft package. Composite sampling, comprising a grid of measured elevation values supplemented by heights measured along rivers, watersheds, and terrain break lines, is carried out manually by photogrammetric operators to form a digital elevation model (DEM). The final output is a hardcopy ortho-image produced at 1:50,000 scale from a film transparency using a Wild OR-1 analytically controlled orthophoto printer, together with a contour plot derived by interpolation from the DEM data. It should be said that difficulties have been experienced with orientation and plotting when the individual SPOT images making up the stereo-pair have been acquired some months apart, e.g., at the beginning and the end of the rainy season. These result in the very different appearance of vegetation, cultivated areas, and water bodies in the corresponding images, resulting in problems with stereo-viewing and orientation. By contrast, the areas mapped in Yemen (by OSI), in Djibouti (by IGN), and in Saudi Arabia (by MSD) were mostly desert or semi-arid terrain and far fewer difficulties of this type have been encountered.

Notwithstanding the difficulties, the use of SPOT stereo-pairs as an economic method of topographic map production at small scales for the huge areas of arid and semi-arid ter-
Digital Photogrammetric Techniques Applied to SPOT Stereo-Imagery

Over the last few years, there has been a noticeable trend for suppliers of image processing systems for use with remote sensing imagery to become involved with digital photogrammetry. In particular, given their interest, expertise, and experience in handling remotely sensed imagery, they have developed systems to handle SPOT stereo-imagery. However, this approach has been substantially different from that described above using manual measurements of hardcopy images in an analytical plotter. By contrast, it involves the use of digital image data in conjunction with automatic image matching techniques to produce DEMs and ortho-images to act either as direct input to a GIS system or as the basis for the production of hardcopy image maps or line maps. This is aimed not only at national mapping agencies but also at the geoscience, geophysical, and geocartographic communities who have needs for the rapid generation of DEMs and ortho-images in remote arid areas, for which neither maps exist or access to them is restricted by security considerations.

This paper is concerned with the geometric accuracy testing and with the production and validation of DEMs and ortho-images from SPOT stereo-pairs over a test field which has been established in the Red Sea area. In particular, it reports on the results achieved using the EASI/PACE package produced by PCI in Canada which has fused together the two closely related technologies of remote sensing and photogrammetry for use with SPOT stereo-pairs.

Mathematical Model

The mathematical model which underlies and forms the basis of the analytical photogrammetric solutions adopted in the EASI/PACE package is based on the work originally carried out by Guichard (1983) and Toutin (1985) and since developed further by Toutin (1995) at the Canada Centre for Remote Sensing (CCRS). It employs the well known collinearity equations of photogrammetry which relate corresponding points in the image space and object space through the perspective center of the imaging sensor. However, these equations have been adapted and formulated to suit the geometry of linear array (pushbroom) scanners such as SPOT in which each line of the scanner image has an individual and different perspective center, instead of the single perspective center for a whole image that exists with the frame photographs generated by aerial or space cameras.

Besides the need to estimate and reconstruct the three-dimensional (3D) coordinates of the individual perspective center for each individual line of a linear array image, it is also necessary to take account of the changing attitude of the satellite and its sensor over the time period during which the SPOT image has been acquired. This is achieved through the modeling of the satellite orbital path in space by combining the satellite's positional and velocity vector with the changing attitude of the platform to generate the exterior orientation parameters for the linear array image. Thus, the model takes into account both the displacements due to the dynamically changing platform and sensor motion and orientation and those arising from sensor geometry due to the physical characteristics of the Earth (rotation, curvature, and ground relief). The model has also been developed to take into consideration the geoid and the ellipsoid used in the area over which the image has been acquired and the relevant cartographic projection system such as UTM.

Thus, the general form of the collinearity equations that perform the transformation between the image coordinates and the map reference system is as follows (Toutin, 1985):

\[
P_p + y(1 + \delta y - \tau) - H_0 \Delta R^* = 0; \]

\[
X + \theta \frac{H}{\cos \chi} + \alpha (Q + \theta x - \frac{H}{\cos \chi}) - Q \Delta R = 0.
\]

with

\[
X = (x - \alpha y)(1 + \frac{h}{N_0}) + by^2 + cxy
\]

and

\[
H = h - \frac{x^2}{2N_0^2}.
\]

Each parameter is given by a mathematical formula that represents the physical realities of the viewing geometry, including the satellite, the Earth, and the geographical position of the scene. These are as follows:

- \( P \) and \( Q \) are scale factors in \( Y \) and \( X \), respectively;
- \( \theta \) and \( \tau \) are a function of the leveling angles in \( X \) and \( Y \), respectively;
- \( \alpha \) is a function of the rotation of the Earth;
- \( H_0 \) is the satellite elevation at the centerline;
- \( N_0 \) is the normal to the ellipsoid;
- \( \chi, \delta y, b, \) and \( c \) are the known second-order parameters which are a function of the satellite, the scene center, and the Earth's center geometry;
- \( \Delta R^* \) and \( \Delta R \) are the non-linear variations in attitude;
- \( p \) and \( q \) are the image coordinates; and
- \( x, y, \) and \( h \) are the ground coordinates in an intermediate reference system.

Because of the close correlation of several of the exterior orientation parameters, e.g., those related to adjacent lines within the SPOT image, it is possible with this model to combine and integrate several of these parameters into a single term so that only a relatively small number of parameters need to be solved for. Thus, in practice, only eight independent parameters have to be determined with the model (Toutin, 1985). These comprise five of the above terms — the two scale factors \((P \) and \( Q)\) along the \( Y \) and \( X \) coordinate axes of the image; the two leveling factors \((\theta \) and \( \tau)\) which are functions of the attitude or rotation angles around the \( X \) and \( Y \) axes; and the remaining factor, \( \alpha \), which is mainly a function...
of the Earth’s rotation—all of which are determined by means of a least-squares solution using the collinearity equations. The remaining three parameters relate the local terrain (or object) coordinate system to the cartographic projection system.

The minimum number of ground control points (GCPS) needed to effect a photogrammetric solution for each image is, therefore, four (Toutin and Carbonneau, 1989; Toutin and Carbonneau, 1990); any redundancy above that number is taken care of by the least-squares solution. In practice, it is normal to use more GCPS than the minimum in order to overcome or minimize the effects of small errors in point identification and measurement and to obtain the best estimate for the values of the exterior orientation parameters and attitude data. The inputs to the module comprise the orbital parameters generated by the satellite ephemeris (which are provided from the header file that accompanies the SPOT image data); plus the measured image coordinates (in the form of their pixel row and column values) and the corresponding terrain coordinates (E,N,H) of the ground control points. A separate modeling and photogrammetric solution is generated for each of the individual images which go to make up the stereo-pair formed by the overlap of the two cross-track images taken from quite different orbital paths (Figure 1).

**SPOT Level 1A and Level 1B Images**

Consideration must also be given to the fact that the image data can be ordered and supplied by the various SPOT processing facilities in a variety of formats with widely differing degrees of processing and accuracy. The two most commonly supplied are the so-called Level 1A and 1B formats. In the former case (Level 1A), the SPOT images only have radiometric processing applied to them; i.e., they are not corrected geometrically, nor are they resampled and the actual image area remains constant at 6,000 by 6,000 pixels. With nadir images (as required for stereo coverage), the area covered by each individual pixel will vary in the cross-track direction and results in the panoramic effect typical of tilted images. In the latter case (Level 1B), the images have substantial geometric processing applied to them, including corrections for Earth rotation, tilt angle, etc. This results in an image which approximates that of a map, though it still contains the displacements due to the terrain relief. The end result is a resampled image with a constant pixel size (10 m in the case of SPOT Pan images) and an increased number of pixels (up to 8,500) in the cross-track direction, depending on the degree of tilt. The basic Level 1A image is that considered in the mathematical modeling discussed above and is that usually preferred by photogrammetrists for utilization both in analytical plots and in digital image processing systems handling SPOT stereo-pairs. However, the Level 1B images are supplied to the geoscience community in quite large numbers, partly on account of its geometry being approximately orthographic and therefore more “map-like,” but also as a result of the commercial pricing policies operated by SPOT Image’s facility in France whereby the Level 1B images acquired pre-1990 are available at much lower prices than those charged for Level 1A images.

In view of this, the EASI/PACE module has to be able to handle both commonly used Levels of SPOT imagery. The approach taken by PCI is to standardize on the Level 1A solution and to convert each Level 1B image back to its equivalent Level 1A form so that it utilizes the same solution. In fact, the generation of the Level 1B image had been carried out by the SPOT processing facilities in France using a third-order polynomial until the autumn of 1995, and by a fifth-order polynomial since then. Thus, the required conversion within EASI/PACE is achieved utilizing the parameters employed in the initial polynomial transformation from Level 1A to 1B (which are available in the image header file) in a reverse transformation. Thereafter, the program written for the implementation of the Level 1A modeling and photogrammetric processing can be used.

**Characteristics of the EASI/PACE System**

The mathematical model and photogrammetric solution described above has been used in the development of a satellite DEM and orthorectification module within the overall PCI EASI/PACE system (Cheng and Toutin, 1995). This is based on a pre-operational software package developed by the Department of Natural Resource in Canada (Toutin and Carbonneau, 1992) and licensed to PCI through CCRS. EASI/PACE is a well established image processing package which features the radiometric and geometric preprocessing of a wide variety of remotely sensed images together with the classification of land-cover types, etc., traditionally associated with such packages. It is available on a wide variety of computing platforms, including PCs (running Windows 3.1, 95, and NT and OS/2), Unix-based graphics work stations (e.g., from Sun, SGI, DEC, HP, IBM, and DG), DEC VAX/VMS systems, and the Apple Macintosh. In addition to the module that executes satellite DEM extraction and orthorectification, which is the main concern of the present paper, a quite separate and complementary module implements the orthorectification of aerial photographs using a DEM, which can either be extracted from the overlapping stereo-pairs of photographs or is supplied from some other source such as an existing DEM derived from contour maps (Cheng and Stohr, 1996; Stohr et al., 1996).

With the SPOT module, in the initial stages, each of the linear array images making up the stereo-pair is handled separately. Thus, each SPOT image is fitted individually to the ground control using a separate space resection based on the available GCPS; thus, the measurements are made monocularly on each of the images. At this stage, the fit of the image to the GCPS after this analytical rectification procedure (called SMOOLED in EASI/PACE) is then declared to the user in terms of the residual errors in the planimetric coordinates (ΔX, ΔY or Δx, Δy) both for the GCPS and any available check points. The next step is to rectify the right image only, leaving

Figure 1. Formation of SPOT stereo-model from overlapping cross-track images.
the left image unrectified. The rectified right image is transformed and resampled to give it a quasi-epipolar geometry. An automated image matching procedure is then used to produce the DEM through a comparison of the respective grey values on each of these images. This procedure utilizes a normalized cross-correlation matching method to match the corresponding pixels in the left image and the rectified right image using the statistics collected in defined windows. Matching is performed by considering the neighborhood surrounding a given pixel in the left image (thus forming a template) and moving this template within a search area on the rectified right image until a position is reached which gives the best match. The actual matching method employed generates correlation coefficients between 0 and 1 for each matched pixel, where 0 represents a total mismatch and 1 represents a perfect match. A second-order surface is then fitted around the maximum correlation coefficients to find the match position to a sub-pixel accuracy. The difference in location between the center of the template and the best matched pixel position gives the disparity or parallax arising from the terrain relief, which an analytical photogrammetric solution using space intersection then converts to absolute elevation values above the local mean sea level datum.

The advantage of using this procedure is that effectively the search for the matching pixels is limited to the quasi-epipolar line on the rectified image, thus greatly improving the algorithm’s efficiency and accuracy. A further advantage arising from the matching method used is that it tolerates any spatially invariant, linear radiometric relationship between the two images.

In this way, a digital elevation model (DEM) is created for the whole of the area covered by the SPOT stereo-pair. A suite of DEM editing tools is available within EASI/SPACE comprising interpolation, filtering, and smoothing functions. Once the elevation values have been determined correctly for the whole stereo model, they can be used to generate contour plots, perspective views, block diagrams, etc., to represent the terrain relief. Also, the DEM data can be employed in the differential rectification and correction of one of the SPOT images in the stereo-pair to the geometry of a map, in which case it then becomes an ortho-image. EASI/SPACE has some limited stereo-viewing capabilities using the anaglyptic method, but, at present, it has no stereo-monsouring capabilities to allow the 3D measurement of GCPs or the correction of erroneous elevation values in the DEM. However, it is planned to introduce these features during 1997.

Test Area
The opportunity has arisen to carry out extensive tests of the geometric accuracy of the SPOT modeling and the program implementing the analytical photogrammetric solutions to produce the DEM and ortho-image; to validate the resulting DEM and ortho-image; and to evaluate the operational status of the EASI/SPACE satellite DEM and orthorectification module. These tests have been undertaken over a very accurate test field located in Jordan. This forms part of an interdisciplinary scientific study of part of the Badia area of northeastern Jordan. This 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 ortho-image mosaic for the whole of the large area covered by the Project (amounting to 12,000 km²) is intended to form part of the topographic database 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 area covered by the SPOT models is mostly a stony desert with an old lava flow covering a large 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., in the northwest corner of the Project area. The ground slopes in a fairly regular manner from northwest to southeast 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. The highest point in the area is a mountain (a former volcano) called Jebel Al-Arab which lies in the northwest corner of the area just across the border into Syria and has an elevation of about 2,000 m. The lowest point is located in the southern part of the area and has an elevation value of around 500 m. Thus, there is an elevation difference of 1,500 m across the Project area covered by the SPOT stereo-models.

Test Material and Data
The test material consists of a block of five SPOT Pan Level images of the area, with a 10 m pixel size covering the whole of the Badia Project area, comprising scenes 122/285, 123/285, 124/285, and 124/286. In addition, a single Level 1A stereo-pair was also purchased for comparative purposes for scene 122/285 which has acted as the main test model. All of these scenes are of a good image quality, being free from the dust and haze which spoils many of the satellite images of the area. Also, the individual images comprising each stereo-pair have been taken with only a small time gap (one to three months) between them, so there are no difficulties arising from changes in the appearance of the vegetation, cultivated areas, and water bodies which might cause problems in measuring the ground control points and in forming and viewing the stereo-models and in extracting heights from them. Furthermore, all of these SPOT stereo-pairs possess an excellent base-height ratio (0.86 to 0.98) which promised 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 12 dual-frequency geodetic quality sets. The planimetric (xu, yu) and height (z) accuracies in terms of the RMSE values for each of the GCPs are all 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 (Figure 2).

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 four different systems:

- WGS84 geocentric coordinates,
- geographical (latitude/longitude) values,
- Universal Transverse Mercator (UTM) values, and
- Jordan Transverse Mercator (JTM) values — the national system used in Jordan.

The UTM values are those used in the tests described in this paper.

Besides the very accurate field of control points set up by RJGC, the Centre has also made available digitized versions of the existing topographic maps covering the Badia Project area at both 1:250,000 and 1:50,000 scales with the appropriate contour intervals (50 m and 20 m, respectively).
resection and analytical rectification, while the second group were not used in the analytical solution to determine the parameters. Both the Level were not used in the analytical solution to determine the parameters. Both the Level acted purely as independent check points whose coordinates acted purely as independent check points whose coordinates were not used in the analytical solution to determine the coordinates. Thus, the contours and the profiles are available to validate the DEM data produced by the EASI/PACE package.

Test Results — Exterior Orientation and Analytical Rectification Using EASI/PACE
The measurements of the corresponding image coordinates on the two overlapping images making up each stereo-pair were made monoscopically using Version 6.0.1 of the PCI EASI/PACE system running under the Windows 3.1 operating system on a PC equipped with a 133-MHz Pentium processor, 32 Mbytes of RAM, and 4 GBytes of hard disk. The precision of pointing during the monoscopic measurements is estimated to be half-a-pixel. The results of the analytical rectification of the individual component images of each of the SPOT Level 1B stereo-pairs, in terms of their fit to the ground control points and the resulting residual errors in $\Delta E$ and $\Delta N$, are set out in Table 1.

As can be seen from the table, the results for the five SPOT stereo-pairs show a fairly consistent pattern, with an average RMSE value of around $\pm 6$ m for the residual errors in both the $\Delta E$ and $\Delta N$ directions and an average RMSE value for planimetry ($\Delta P$) of $\pm 8.5$ m — which lies just below the single pixel value of 10 m. The results for the single Level 1A stereo-pair covering Scene 122/285 are only slightly better with an RMSE value for the planimetric accuracy ($\Delta P$) of $\pm 7$ m.

In the case of the main stereo-pair (122/285), because many more GCPs were available, a further test was carried out dividing these into two groups in different combinations. The first group acted purely as control points for the space resection and analytical rectification, while the second group acted purely as independent check points whose coordinates were not used in the analytical solution to determine the parameters. Both the Level 1A and 1B stereo-pairs were tested in this way. Again a comparison was made for both the control points and the check points between the given GCP coordinate values determined by the ground survey using differential GPS and the corresponding values derived from the analytical resection. The RMSE values of the residual errors were again determined and are shown in Table 2.

Inspection of the RMSE values for the residual errors at the check points given in Table 2 shows that as few as ten accurately fixed control points produce little or no change in the overall size of the errors occurring at the independent check points. Even with as few as five well-chosen control points, there is only a small increase in the size of the errors at the check points. It should be noted that the drop in the RMSE error values at the control points when only five such points are used is solely a consequence of the lack of redundancy in the least-squares solution when so few points are being used in the analytical solution.

As can be seen from the vector plots for the left and right images (Figure 3) of the Level 1B stereo-pair for Scene 122/285, the pattern of the residual errors in planimetry is mostly random, with only a few areas where the errors exhibit a slight systematic pattern locally.

It is interesting to note that still better results have been achieved by Cheng and Toutin (1996) in tests of a single SPOT Pan Level 1A image (not a stereo-pair!) over a test area in Irvine, California using the same analytical rectification procedure and solution of EASI/PACE. For this test, the GCPs were extracted from the USGS 1:24,000-scale topographic maps of the Irvine area. A summary of the results is given in Table 3. This confirmed previous results carried out on three Level 1A images of OCS (Toutin and Carbonneau, 1989; Toutin and Carbonneau, 1990).

Table 1. RMSE Values for Residual Errors at the GCPs for the Five SPOT Level 1B Stereo-Pairs Covering the Badia Project Area

<table>
<thead>
<tr>
<th>Scene No.</th>
<th>No. of GCPs</th>
<th>Left Image No.</th>
<th>Left Image</th>
<th>Right Image No.</th>
<th>Right Image</th>
<th>No. of GCPs</th>
<th>Left Image No.</th>
<th>Left Image</th>
<th>Right Image No.</th>
<th>Right Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>122/285</td>
<td>48</td>
<td>$\pm 8.3$</td>
<td>$\pm 7.5$</td>
<td>$\pm 11.2$</td>
<td>$\pm 8.3$</td>
<td>$\pm 9.3$</td>
<td>$\pm 12.4$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>123/285</td>
<td>18</td>
<td>$\pm 5.0$</td>
<td>$\pm 6.6$</td>
<td>$\pm 8.3$</td>
<td>$\pm 3.9$</td>
<td>$\pm 8.6$</td>
<td>$\pm 9.5$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>124/285</td>
<td>18</td>
<td>$\pm 4.7$</td>
<td>$\pm 3.5$</td>
<td>$\pm 5.9$</td>
<td>$\pm 4.7$</td>
<td>$\pm 4.5$</td>
<td>$\pm 6.5$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>125/285</td>
<td>20</td>
<td>$\pm 6.0$</td>
<td>$\pm 6.0$</td>
<td>$\pm 8.4$</td>
<td>$\pm 6.0$</td>
<td>$\pm 5.8$</td>
<td>$\pm 8.3$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>126/285</td>
<td>12</td>
<td>$\pm 7.1$</td>
<td>$\pm 5.3$</td>
<td>$\pm 6.9$</td>
<td>$\pm 8.9$</td>
<td>$\pm 6.5$</td>
<td>$\pm 10.6$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean RMSE Value $= 6.2 \pm 5.8 \pm 8.5 \pm 6.2 \pm 6.9 \pm 9.5$

Table 2. RMSE Values for Residual Errors at the Control Points and Check Points for the Reference Scene 122/285 Over the Badia Test Field

<table>
<thead>
<tr>
<th>Control Points</th>
<th>Check Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level Image No.</td>
<td>$\Delta E$ (m)</td>
</tr>
<tr>
<td>1A Left</td>
<td>$\pm 8.7$</td>
</tr>
<tr>
<td>Right</td>
<td>$\pm 7.7$</td>
</tr>
<tr>
<td>1B Left</td>
<td>$\pm 8.7$</td>
</tr>
<tr>
<td>Right</td>
<td>$\pm 7.7$</td>
</tr>
<tr>
<td>2A Left</td>
<td>$\pm 5.6$</td>
</tr>
<tr>
<td>Right</td>
<td>$\pm 5.6$</td>
</tr>
<tr>
<td>2B Left</td>
<td>$\pm 8.9$</td>
</tr>
<tr>
<td>Right</td>
<td>$\pm 5.4$</td>
</tr>
<tr>
<td>3A Left</td>
<td>$\pm 3.6$</td>
</tr>
</tbody>
</table>
TABLE 3. RMSE VALUES FOR RESIDUAL ERRORS AT THE CONTROL POINTS AND CHECK POINTS FOR THE SPOT LEVEL 1A SCENE OF IRVINE, CALIFORNIA

<table>
<thead>
<tr>
<th>Control Points</th>
<th>Check Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>$\Delta E$ (m)</td>
</tr>
<tr>
<td>10</td>
<td>$\pm 3.3$</td>
</tr>
</tbody>
</table>

From Table 3, it can be seen that the planimetric errors ($\Delta L$) in terms of the RMSE values at the control and check points were $\pm 4.2$ m and $\pm 4.7$ m, respectively. It should be noted that the GCPS used in the Irvine test were very well defined points such as road and street intersections, whereas the points used in the Badia test field were the much less well defined features typical of a desert area.

**Absolute Orientation**

As noted earlier, the photogrammetric approach used in the EASI/PACE satellite DEM and Ortho module utilizes the monoscopically measured image coordinates of the GCPS and determines the parameters of the exterior orientation by employing an analytical resection of each of the individual images making up the stereo-pair. However, as a result of the experience gained in the present project, PCI has now provided an absolute orientation of the stereo-pair to check the fit of the photogrammetrically determined values of the GCPS — in particular, the elevation values — with those determined from the GPS survey. This uses the measured image coordinates and the exterior orientation parameters (comprising the perspective center coordinates and values of the attitude parameters) determined from the individual analytical resections to carry out a space intersection and compute the 3D terrain coordinates of the GCPS. These are compared with the corresponding terrain coordinates measured by GPS.

The results in both planimetry and height from the absolute orientation are given for all five stereo-models in Table 4 using all the GCPS available in each model.

In Table 5, a further and more detailed set of results is presented for the main reference stereo-pair (122/285) where the largest number of GCPS was available. These were divided into two groups — control points (used for the absolute orientation) and independent check points (used for accuracy checking) — with varying numbers of points used in each group in separate tests. Both the Level 1A and 1B versions of the stereo-pair were checked in this way.

It will be seen from Table 4 that the RMSE values in elevation (AH) lie in the range $\pm 4.4$ m to $\pm 7.7$ m when all the available GCPS were used for the absolute orientation. Table 5 shows that the RMSE values in elevation (AH) at the independent check points lie between $\pm 5.1$ m and $\pm 5.7$ m for the SPOT Level 1B stereo-model tested. In fact, this gives a slightly better result than that obtained for the corresponding Level 1A stereo-pair where the RMSE values in elevation (AH) lie between $\pm 6.0$ m and $\pm 6.4$ m.

**Results of Geometric Accuracy Test Using the University of Glasgow 3D Spatial Solution**

A parallel set of geometric accuracy tests with the SPOT Level 1B stereo-pairs has been carried out using the analytical photogrammetric solution developed quite independently at the University of Glasgow by one of the authors (M.J. Valadan Zoej). This solution is also based on the use of an orbital parameter model, but it does not carry out the resampling after analytical resection of the individual SPOT images as implemented in the EASI/PACE solution, nor does it have the DEM and orthorectification capability of the latter. Instead, the Glasgow solution is purely an analytical photogrammetric procedure which, after the determination of the exterior orientation parameters from space resection, carries out the point determination of the GCPS from the measured image coordinates using a space intersection (3D) solution. However, the actual measurements of the image points have been carried out using the EASI/PACE system. The results from these tests are given in Table 6.

For the main test stereo-model, 122/285, a further 23 GCPS have been used as independent check points distributed over the area of the model. The RMSE values at these check points in terms of their X, Y, and Z coordinates are as follows:

![Figure 3](image-url)

Figure 3. (a) Vector plot of the planimetric (X/Y) errors at the control points and check points for the left image of Level 1B stereo-pair 122/285 using EASI/PACE. (b) Vector plot of the planimetric (X/Y) errors at the control points and check points for the right image of Level 1B stereo-pair 122/285 using EASI/PACE.
The vector plots (Figure 4) show that the individual residual errors are random both in extent and in direction.

**DEM Extraction**

As mentioned earlier, the procedure employed for image matching in **EASI/PACE** is to proceed to the image matching stage using the rectified and resampled data produced after the analytical resection has been completed. This involves the matching of the density or grey level values on the two images comprising the stereo-pair. These produce disparities or parallax values which are converted to elevation values using the exterior orientation parameters determined by the analytical resection (**SMODEL**). This produces a regular grid of elevation values which are extracted to form the DEM for the terrain covered by the stereo-pair. The local fit, i.e., the relative accuracy of this net of elevation values, was usually good — for the Badia test models, RMSE values of ±3 to 4 m in elevation (ΔH) at the GCPS were normal. However, it must be noted that these values were not determined from the measured image coordinate values of the GCPS carried out for the resection procedure, but purely from the disparities generated during the subsequent image matching procedure carried out for the DEM extraction.

With regard to the automatic extraction of the elevation values for each of the Level 1B stereo-pairs using image matching, this has been proven to work well. In spite of the almost complete lack of cultural detail in this desert area, the matching algorithm has worked extremely reliably and has produced elevation values for 98 percent of the Badia Project area with only a few gaps or holes where correlation had failed, e.g., in shadow areas lacking texture. EASI/PACE 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 overlaps 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, the

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**Table 4.** RMSE VALUES FOR THE RESIDUAL ERRORS AT THE GCPS AFTER ABSOLUTE ORIENTATION FOR THE FIVE SPOT LEVEL 1B STEREO-PAIRS COVERING THE BADIA PROJECT AREA

<table>
<thead>
<tr>
<th>Scene ID</th>
<th>B/H ratio</th>
<th>No. of GCPS</th>
<th>ΔX(m)</th>
<th>ΔY(m)</th>
<th>ΔP(m)</th>
<th>ΔZ(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>122/285</td>
<td>0.975</td>
<td>48</td>
<td>±4.7</td>
<td>±4.9</td>
<td>±6.8</td>
<td>±4.7</td>
</tr>
<tr>
<td>123/285</td>
<td>0.858</td>
<td>22</td>
<td>±3.8</td>
<td>±4.3</td>
<td>±5.5</td>
<td>±5.8</td>
</tr>
<tr>
<td>123/286</td>
<td>0.858</td>
<td>29</td>
<td>±4.2</td>
<td>±5.6</td>
<td>±7.0</td>
<td>±4.4</td>
</tr>
<tr>
<td>124/285</td>
<td>0.975</td>
<td>19</td>
<td>±4.8</td>
<td>±5.3</td>
<td>±7.1</td>
<td>±7.7</td>
</tr>
<tr>
<td>124/286</td>
<td>0.975</td>
<td>13</td>
<td>±3.2</td>
<td>±5.5</td>
<td>±6.3</td>
<td>±4.6</td>
</tr>
</tbody>
</table>

ΔX = ±8.9 m; ΔY = ±8.2 m; and ΔZ = ±10.0 m.

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**Table 5.** RMSE VALUES FOR THE RESIDUAL ERRORS AT THE CONTROL POINTS AND INDEPENDENT CHECK POINTS FOR THE REFERENCE STEREO-PAIR 122/285 OVER THE BADIA TEST FIELD

<table>
<thead>
<tr>
<th>Control Points</th>
<th>Check Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level No.</td>
<td>ΔE(m)</td>
</tr>
<tr>
<td>1A</td>
<td>32</td>
</tr>
<tr>
<td>1B</td>
<td>22</td>
</tr>
<tr>
<td>21</td>
<td>32</td>
</tr>
<tr>
<td>13</td>
<td>33</td>
</tr>
<tr>
<td>23</td>
<td>47</td>
</tr>
<tr>
<td>13</td>
<td>3.2</td>
</tr>
</tbody>
</table>

---

**Table 6.** RMSE VALUES FOR RESIDUAL ERRORS AT THE GCPS FOR THE FIVE SPOT LEVEL 1B STEREO-PAIRS COVERING THE BADIA PROJECT AREA

<table>
<thead>
<tr>
<th>Scene ID</th>
<th>B/H ratio</th>
<th>No. of GCPS</th>
<th>ΔX(m)</th>
<th>ΔY(m)</th>
<th>ΔP(m)</th>
<th>ΔZ(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>122/285</td>
<td>0.975</td>
<td>15</td>
<td>±5.0</td>
<td>±5.1</td>
<td>±7.1</td>
<td>±6.4</td>
</tr>
<tr>
<td>123/285</td>
<td>0.858</td>
<td>18</td>
<td>±5.2</td>
<td>±5.7</td>
<td>±8.4</td>
<td>±8.3</td>
</tr>
<tr>
<td>123/286</td>
<td>0.858</td>
<td>20</td>
<td>±5.4</td>
<td>±7.4</td>
<td>±9.8</td>
<td>±8.1</td>
</tr>
<tr>
<td>124/285</td>
<td>0.975</td>
<td>13</td>
<td>±8.0</td>
<td>±8.6</td>
<td>±11.7</td>
<td>±13.2</td>
</tr>
<tr>
<td>124/286</td>
<td>0.975</td>
<td>13</td>
<td>±4.8</td>
<td>±9.0</td>
<td>±10.2</td>
<td>±3.3</td>
</tr>
</tbody>
</table>

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![Figure 4](image-url)
merged data set amounts to 534 Mbytes when a 20-m interval (=2 pixels) between the matched points is used. The final merged DEM covers an area roughly 90 by 120 km in size.

Contours may also be derived from the DEM data. A preliminary validation check superimposing the contour lines from the merged DEM of the Badia area over the contours derived from the 1:250,000-scale topographic map of the area shows an excellent agreement between the two (Figure 5), both for the 20-m and 50-m contour intervals. A further check at over 400 positions comparing the elevation values provided by the digitized contours from the existing map with the elevation values produced by the SPOT DEM for the reference scene (122/285) produced RMSE values (ΔH) of ±8.3 m for the Level 1A stereo-pair and ±9.2 m for the Level 1B stereo-pair. Further work on the validation of the DEM of the Badia Project area using the elevation profiles measured by kinematic GPS techniques across the area is now under way.

For the Level 1A stereo-pair covering the area around Irvine, California, already discussed above, a similar comparison of the spot heights given on the USGS map with the elevation values given by the DEM had been made previously (Cheng and Toutin, 1994). This resulted in RMSE values in elevation (ΔH) of ±9.6 m at the GCPs and ±13.4 m at the independent check points. However, the Irvine area contains a great deal of forested mountainous terrain, for which a lower accuracy is to be expected as compared with the desert terrain of the Badia area.

Indeed, it must be made clear that, because it is an area of stony desert with little vegetation, the Badia test area is especially suited to the automatic generation of DEM data from SPOT stereo-pairs. In other areas, where there are strong shadows or occluded areas or in areas where there are considerable changes in the vegetation cover, cultivated areas, or hydrology between seasons, giving rise to substantial differ-

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**Figure 5.** Contours at a 50-m contour interval derived from the seamless elevation model of the Badia Project area formed from the individual DEMs generated from the five SPOT Level 1B stereo-pairs using EASI/PACE. These have been superimposed on the contours digitized from the existing 1:250,000-scale topographic map of the area and show excellent agreement.

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**Figure 6.** "Fishnet-type" perspective block diagram of part of the Badia Project area constructed from the DEM generated by the PC-based EASI/PACE system.
ences in the appearance of a specific area on the individual scenes making up the SPOT stereo-pair (Petrie and Liwa, 1995), it may be impossible to carry out the image matching procedure successfully over large parts of the area covered by the stereo-pair.

Besides the contour plots, various other products can be derived from the DEM by the EASIIPACE package, including "fishnet-type" perspective block diagrams. An example is included as Figure 6.

Ortho-Image Generation

The DEM data set also forms part of the base data required for the orthorectification process. First an ortho-image has been generated from each individual Level 1B stereo-pair; later, these have all been merged together using the facilities provided by the EASIIPACE module to form a single seamless ortho-image mosaic amounting to 56 Mbytes of data using a pixel size of 20 m. 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 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. Figure 7 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 ortho-image, a check was carried out by measuring quite independently on the ortho-image 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 in $\Delta E$ and $\Delta N$ were ±8.7 m and ±8.8 m, respectively, which, for the 20-m pixel size used to produce the final ortho-image, gives RMSE values of ±0.44 pixels in both the $x$ and $y$ directions on the ortho-image. The vector plot of the individual residual errors resulting from the 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.

Conclusion

From the test results given above, it is apparent that, in terms of geometric accuracy, the modeling of the SPOT orbit and the photogrammetric solution utilized by the EASIIPACE system produces an acceptable result for topographic mapping at small scales within a fully digital photogrammetric environment. Furthermore, the DEM extraction and orthorectification module based on the use of automatic image matching techniques has worked in a thoroughly satisfactory manner to produce an acceptable contour plot and ortho-image mosaic for a very large area of desert terrain using SPOT Level 1B stereo-imagery. This is particularly encouraging because this type of image is in widespread use among the geoscience, geophysical, and geoeexploration communities, rather than the Level 1A stereo-imagery which is favored by the photogrammetric community. However, the results are also
highly relevant to the topographic mapping community concerned with the image mapping of large areas of arid and semi-arid terrain.

Acknowledgments
The authors wish to thank Dr. R. Dutton of CORD and Mr. M. Shahbaz of HCST, the Co-Directors of the Badia Project, for all their assistance with this part of the overall Project. Also, Brigadier Salim Khalifa, the Director of the RJGC, must be thanked for his excellent cooperation, 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.

References

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