SPOT REVISITED: ACCURACY ASSESSMENT, DEM GENERATION AND VALIDATION FROM STEREO SPOT 5 HRG IMAGES

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Abstract

SPOT 5 HRG Level 1A and 1B stereo scenes covering Zonguldak testfield in north-west Turkey have been analysed. They comprise the left and right image components with base to height ratio of 0.54. The pixel size on the ground is 5 m. The bundle orientation was executed by the PCI Geomatica V9.1.4 software package and resulted in 3D geopositioning to sub-pixel accuracies in each axis provided that at least six control points were used in the computation. Root mean square error (rmse) values and vectors of residual errors for Levels 1A and 1B are similar, even for different control and check point configurations. Based on the scene orientation, Level 1A and 1B digital elevation models (DEMs) of the testfield have been determined by automatic matching and validated by the reference DEM digitised from the 1:25 000 scale topographic maps, interferometric DEMs from Shuttle Radar Topography Mission (SRTM) X- and C-band SAR data and the GPS profiles measured along the main roads in the testfield. Although the accuracies of reference data-sets are too similar to the generated SPOT DEMs, these are the only high quality reference materials available in this area. Sub-pixel height accuracy was indicated by the comparison with profile points. However, they are in favourable locations where matching is always successful, so such a result may give a biased measure of the accuracy of the corresponding DEMs.

Keywords: automatic image matching, DEM generation and validation, geometric accuracy testing, SPOT 5 HRG Level 1A and 1B stereo-images

INTRODUCTION

Among the sources of satellite imagery that are available in the market, SPOT has always been popular with the photogrammetric community especially for use in 3D topographic mapping. A detailed review of published results on the geometric accuracy and digital elevation model (DEM) generation/validation from earlier SPOT missions was carried out by
Al-Rousan (1998). Further, in the same study and other related publications (Al-Rousan et al., 1997; Al-Rousan and Petrie, 1998; Valadan Zoej and Petrie, 1998), the similar capabilities of SPOT stereopairs with most commonly used formats of Levels 1A and 1B were investigated using digital workstations. Such a level of experience provides good knowledge about what can or cannot be achieved by earlier SPOT sensors. However, there is now a new satellite available in the SPOT series: SPOT 5.

The SPOT 5 satellite includes the imaging instruments known as High Resolution Geometric (HRG), High Resolution Stereoscopic (HRS) and Vegetation. A pair of HRG pushbroom scanners operating side by side provide panchromatic images with 5 m ground pixel size in the standard mode and 2·5 m in “supermode” while maintaining the 60 km swath width of the previous SPOT satellites. However, a major innovation for SPOT 5 is the HRS imager with its along-track stereo capability, designed specifically to produce DEMs over a 120 km swath. The satellite also carries the same low-resolution (1 km ground pixel), wide swath (2200 km) vegetation imager with four spectral bands as used on SPOT 4 (which is also still operational).

Many publications by French scientists cover the SPOT 5 mission. Rouziès et al. (1999), Fratter et al. (2001), Fontannaz and Begni (2002) and Gleyzes et al. (2003) give overviews of the system and its products. Breton et al. (2002), Bouillon et al. (2003), Lebègue et al. (2003) and Léger et al. (2003) discuss the image quality as well as pre-flight and in-flight radiometric and geometric calibrations. However, up until now relatively little has been published concerning orientation accuracy or DEM generation and validation procedures for the HRG sensor. Nonin and Piccard (2003) tested the orientation and DEM accuracy of 10 stereopairs with the standard and supermode using different base to height ($B/H$) ratios ranging from 0·12 to 0·84 and time lags between the two acquisitions using an internal software package. For the orientation of HRG images, they stated that “with 81 GCPs, the global accuracy in $X$, $Y$ and $Z$ respectively was 2·41, 2·11 and 2·38 m rms”. In this test, data from an airborne digital scanner HRSC AXW with an accuracy of 0·8 m was used as reference. For the DEM validation, the best result was obtained by a stereopair with smaller time lag (2 days) and $B/H$ ratio of 0·61; in this case, root mean square error (rmse)-$Z$ was found to be 2·89 and 2·60 m in standard and supermode, respectively. Additionally, the authors noticed a strong correlation between the time lag and the quality of the DEM. Vozikis et al. (2003) have evaluated a test on a SPOT 5 HRG supermode image of the Attika testfield in Greece using different sensor orientation models including the direct linear transformation (DLT), affine and parallel perspective model and different coordinate systems (UTM and WGS84 Geocentric). The results were given in the form of rmse values measured in image space. While the DLT and affine models in a geocentric coordinate system produced accuracy results of about 0·9 pixel, it was found to be 2·4 pixels for the parallel perspective model, but this time with UTM projection. In Kornus et al. (2004), the orientation of SPOT 5 HRG supermode imagery was handled by bundle adjustment using a functional model based on correction polynomials. It resulted in an rmse value of about 2 m in Easting, Northing and Height at 17 check points. Additionally, DEMs were produced by a region-growing algorithm for four test sites (as selected sub-scenes from the entire image) including mountainous, moderate and urban terrain types. The comparison with a DEM of 15 m grid size and 1·1 m accuracy yielded standard deviations better than 5 m in flat and moderate terrain and better than 10 m in mountainous regions. An additional DEM covering the whole scene (approx. 60 km × 80 km) was generated with a standard deviation of approximately 8 m using commercial ISAE software and rational functions.

However, in this paper, the authors report on the results of sensor orientation, DEM generation and validation approaches for SPOT 5 HRG standard mode stereo scenes (processed as Levels 1A and 1B) using the PCI Geomatica V9.1.4 commercial software package. First,
SPOT 5 HRG instruments, image processing levels and the Zonguldak testfield are described, then the application of bundle orientation is explained in detail. This is followed by a discussion of DEM extraction using automatic image correlation. Finally, validation tests of matched DEMs based on the reference data-sets including DEMs digitised from the 1:25 000 scale topographic maps, interferometric DEMs derived from the Shuttle Radar Topography Mission (SRTM) X- and C-band SAR and the GPS profiles measured along the main roads of the testfield.

SPOT 5 HRG Instruments and Image Formats

The characteristics of HRG instruments with their image channels are given in Table I. Two HRG instruments are linear array pushbroom systems providing 5 m sampled images in panchromatic bands known as HMA and HMB. A 2.5 m sampled image in the same panchromatic band is known as THR (Very High Resolution). The two charge-coupled device (CCD) line arrays (HMA and HMB) are shifted one from the other 0.5 pixel in the across-track direction and 3.45 pixels in the along-track direction, making it possible to produce a restored image which has 24 000 pixels with a 2.5 m sampling distance. This is the result of a process called “Supermode” (Latry and Rougeé, 2003). A 10 m sampled image in a multispectral mode called HX corresponding to three spectral bands B1 (green), B2 (red) and B3 (near infrared) and a 20 m sampled image in a SWIR (short wave infrared) band are also available. With the improvement of the resolution, the size of the detectors has decreased, but the number of detectors has increased when compared with SPOT 4, so as to keep the same ground field of view. Both HRG instruments still have a pointing mirror, allowing the viewing angle from nadir to vary within a range of ±27°. This tracking capacity allows high revisit frequency and cross-track stereo-acquisition capability.

As before, SPOT IMAGE is the commercial operator of SPOT 5, programming the satellite, processing the imagery that it acquires and distributing the products to customers. Several levels of processed imagery from this instrument are produced as standard products, Levels 1A and 1B being those most commonly supplied to users. Level 1A is raw data that has been corrected radiometrically, whereas Level 1B data has been corrected additionally for certain known geometric distortions (earth rotation, earth curvature and panoramic effect) and results in a rectified geometry which is more “map-like”. SPOT IMAGE employs a fifth-order polynomial in the conversion of the Level 1A image to a Level 1B image (SPOT Handbook, 2004). Additionally, the company uses a new format called DIMAP (Digital Image MAP) to encode auxiliary data by which images are delivered and directly accessible through standard formats such as GeoTIFF and XML.

Experimental Area

The test site covering a small area around Zonguldak is located in the Western Black Sea region of Turkey. It is noted for being one of the main coal mining areas in the world. Although

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Channel</th>
<th>Spectral band (µm)</th>
<th>Resolution (m)</th>
<th>Detector number</th>
<th>Detector size (µm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRG</td>
<td>HM</td>
<td>0.49 to 0.69</td>
<td>5</td>
<td>12 000</td>
<td>4.5 x 6.5</td>
</tr>
<tr>
<td></td>
<td>THR</td>
<td>0.49 to 0.69</td>
<td>2.5</td>
<td>24 000</td>
<td>4.5 x 6.5</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>0.50 to 0.59</td>
<td>10</td>
<td>6000</td>
<td>13 x 13</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>0.61 to 0.68</td>
<td>10</td>
<td>6000</td>
<td>13 x 13</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>0.78 to 0.89</td>
<td>10</td>
<td>6000</td>
<td>13 x 13</td>
</tr>
<tr>
<td></td>
<td>SWIR</td>
<td>1.58 to 1.75</td>
<td>20</td>
<td>3000</td>
<td>26 x 30</td>
</tr>
</tbody>
</table>
now less economically viable than in the past, there are several coal mines still active in Zonguldak. The area has rolling topography with steep and rugged terrain in some parts. Although urbanised along the sea coast, there are some agricultural lands and forest areas inland. The elevation ranges roughly up to 1800 m. The Zonguldak SPOT 5 HRG images were acquired just 1 day apart on 13th and 14th August 2003. Less than 1% of the imaged area was covered by clouds and atmospheric conditions were almost the same. The scenes were taken with incidence angles of L16/65° and R13-52° resulting in a B/H ratio of 0.54. Fig. 1 shows the left component of the Zonguldak SPOT stereopairs with the location of 48 ground control points (GCPs) used in the bundle adjustment (shown by white crosses). In this figure, the area where the reference data-sets are available for validating the DEM extracted from the SPOT 5 HRG Level 1A and 1B stereopairs is also shown. These data-sets include the reference DEM digitised from the 1:25 000 scale topographic maps (coverage shown by the black polygon) and interferometric DEMs derived from SRTM X-band (the white polygon shows where the X-SAR DEM is available) and C-band SAR (since it is available for the whole image, its coverage is not shown on the figure). All control points and profiles have been measured using a TOPCON TURBO-SII GPS instrument with a static method for relative positioning. The expected accuracy of these observations is in the sub-metre level. Digital image coordinates for these GCPs were measured manually using the GCPWorks module of the PCI photogrammetric system with sub-pixel point location.

**Bundle Orientation by PCI OrthoEngine**

Over the past two decades, various mathematical models have been formulated to derive 3D information from spaceborne linear CCD sensors, especially SPOT, IRS-1C/1D and MOMS because they need a different sensor model from a conventional metric frame camera. These models have been developed using the known sensor information and modified...
collinearity equations, in some cases including parameters for modelling errors in the interior orientation or in-flight calibration, or incorporating orbital information and orbital constraints. The mathematical model which underlies and forms the basis of the photogrammetric solutions adopted in the PCI system is based on the work developed by Toutin (1995) at the Canadian Centre for Remote Sensing (CCRS). This method reflects the physical reality of the complete viewing geometry and compensates for distortions that may occur during image formation (further information may be found at http://www.pcigeomatics.com).

Table II shows the accuracy results obtained using the satellite orbital modelling of the PCI system for SPOT 5 HRG Level 1A and 1B stereo-images. Several tests were carried out by dividing the GCPs into two groups in different combinations. The first group acted as control points while the second group acted as independent check points (ICPs) whose coordinates were not used in the adjustment procedure. For such division, control points were selected in such a way that they surrounded the area of interest. Thus, in this case, they were fairly well distributed over the testfield. In the case of all GCPs being used as control points, the rmse values were acquired in the range of 2.53 to 3.23 m in X, 2.75 to 2.77 m in Y and 3.26 to 3.45 m in Z for both levels. From Table II, it is interesting to note that, in the Y direction, rmse values for ICPs were reduced until approximately 15 GCPs were included in the computation for both levels. Fig. 2(a) and (b) conveys the errors in the form of a vector plot for 1A and 1B, respectively. The black component represents the combined XY error and the grey vector corresponds to errors in height. These diagrams show that the overall representation of error vectors displays a random pattern with groups of points showing locally systematic trends.

Inspection of the rmse for the residual errors at the check points for different GCP/ICP configurations which are given in Table II and shown graphically in Fig. 3 indicates that the rmse values of the residual errors lie in the range ±2.73–2.85 m to ±34.71–35.12 m in
\( X, \pm 2.86 - 3.18 \text{ m to } \pm 12.73 - 12.81 \text{ m in } Y \text{ and } \pm 4.14 - 4.50 \text{ m to } \pm 95.68 - 154.04 \text{ m in } Z. \) In particular, it is clear from Fig. 3 that down to the solution with 35 check points (that is, for solutions using six GCPs or more), accuracy values in each axis are changing smoothly.
However, thereafter, abrupt changes occurred in all axes, but more in the $X$-component. This leads to the conclusion that six control points is the minimum practical number for successful orientation of the imagery.

A comparison of the results obtained from tests carried out on the SPOT Level 1A stereopair with those from the SPOT Level 1B stereopair shows that these various values support one another and the discrepancies between these values are not significant.

**DEM Generation**

Automatic image matching was carried out with the PCI software using an area-based image correlation technique (see Al-Rousan, 1998 for detail) for Level 1A and 1B stereopairs separately. In the DEM extraction menu of the software, there are four critical parameters that the user has to insert: minimum and maximum elevations, “DEM detail” and the pixel sampling interval. The minimum and maximum elevations are used to estimate the search area for the correlation. This increases the speed of the correlation and reduces errors. These values are assigned as 0-00 and 2000-00 m for this process. In the PCI system, matching is a hierarchical approach using a pyramid of reduced resolution images. DEM detail determines how precisely the terrain is to be represented in the DEM. There are three options: High, Medium and Low. For the SPOT process, the High option was selected which means the process continues until correlation is performed on images at full resolution. Pixel sampling controls the size of the pixel in the final DEM relative to input images. The higher the chosen number, the larger the DEM pixel will be, and the faster the DEM is processed. For this experiment, it was taken as 2 pixels, that means, the matched DEM will have a pixel size of 10 m. Fig. 4(a) and (b) shows the grey value representations of resulting SPOT DEMs with the given parameters. During DEM extraction, the PCI system provides an internal DEM report file. This includes: elapsed time required for extraction, maximum and minimum elevations, cell spacing, height residuals at GCPs, average and maximum residuals, rmse values for height and DEM correlation success rate. According to this report file, the rmse in height was found to be ±5-0 m (max. error = 14-8 m) and ±4-1 m (max. error = 10.5 m) derived using the standard formula $\sqrt{\sum(GCP\ elevation - extracted\ elevation)^2/n}$ for DEMs matched using Level 1A and 1B, respectively. DEM correlation success rate is the percentage of pixels that successfully correlated and returned to an elevation value for DEM. The program produced correlation rates of 85 and 84% for Level 1A and 1B processes, respectively. In relation to matching quality, the PCI software generates an additional image channel to represent the correlation score for each DEM pixel. Such an overlay will help to identify pixels where the correlation was weak or failed. Fig. 5(a) and (b) shows the correlation maps for Level 1A and 1B matching processes,

![Fig. 4(a), (b). Grey value-coded form of Level 1A and 1B matched DEMs.](image)
respectively. As can be seen from this figure (also from Fig. 4), areas with forests and high altitude produced lower correlation coefficients and there are several gaps and mismatches on these parts, as well as a couple of positions where clouds are present.

DEM Analysis

To go further and validate the data quality—more especially in terms of geometric accuracy—of the DEMs extracted from SPOT 5 HRG Level 1A and 1B stereopairs of Zonguldak testfield, three different tests have been used:

(i) a comparison of the height values given by the photogrammetrically produced reference maps and the corresponding elevation values given by the matched DEMs;

(ii) a comparison of the height values from the SRTM X- and C-band SAR DEMs and the corresponding elevation values given by the matched DEMs; and

(iii) a comparison of the matched DEMs with the GPS profiles measured along the main roads.

DEM Accuracy—1:25 000 Contour Maps

In this test, the matched DEMs were checked by a reference DEM based on digitised contour lines from the 1:25 000 scale topographic maps. However, only five 1:25 000 sheets were available to construct the reference DEM (hereafter called MAP-DEM) representing the
testfield area and Fig. 6 shows the grey value coded form of this DEM. Although the available sections of the MAP-DEM do not cover the whole model (compare with Fig. 1), coverage did include varying area types, including: urban, open areas with little texture, areas covered by forests, steep and flat areas. That meant that areas of diverse characteristics could be analysed to quantify the accuracy level of the DEM generated by the SPOT 5 HRG Level 1A and 1B stereo-images.

The accuracy of the MAP-DEM was assessed using control points measured by GPS and originally acquired for restituting high-resolution IKONOS images of the test area. Using such GPS-surveyed GCPs, rmse in height was found to be 5.91 m. Additionally, the accuracy of matched DEMs was also checked by the same set of GCPs and rmse-Z values were acquired as 3.91 and 3.14 m for 1A and 1B DEMs, respectively.

Image classification (see Fig. 7) methods were used to separate the forested areas from the DEMs, using a Landsat TM scene of the experimental area. Points within the forest layer were included in the DEMANAL analysis program which has been developed for comparing the SPOT 5 based DEMs with the reference data-sets. With this program, DEM analysis was achieved for forested areas and also for the areas without forest. Furthermore, analysis of DEMs could be achieved for different heights relative to the terrain surface and so the frequency distributions derived from the resultant discrepancies were used to identify specific problems caused by vegetation height. The MAP-DEM corresponds directly to the terrain surface whilst the generated DEMs relate to the visible surface of the vegetation and roofs of buildings.

Based on the comparison of matched DEMs and MAP-DEM, the resulting frequency distributions of height discrepancies for open and forest areas are given in Fig. 8. They represent a normal distribution, but with asymmetry. The acceptable limits of the frequency distribution can be derived from these figures, acceptable limits being 50 m for both open and forest areas with confidence levels very close to or greater than 99%. Apart from this matter, rmse values for open and forest areas are computed and given in Table III. Once bias is removed, accuracy values are in the range of 11.28 to 11.37 m and 12.71 to 12.90 m for the open and forested areas, respectively. In the forest areas, larger height shifts against the MAP-DEM were observed in each case. Also, the accuracy in the forest is not as high as in the open areas due to the limited contrast and the invisible ground surface. Fig. 9 shows, on the left-hand side, the histogram of the SPOT scene taken on 14th August with a mean grey value of 119 and a standard deviation of ±24.3. In a typical forest area the standard deviation of grey

Fig. 7. Forest layer (white parts) of the experimental area showing the same coverage with SRTM C-band DEM.
values is equal to ±6.3. The other scene is very similar. For the open areas, accuracy is also lower compared to the rmse values in height obtained in the bundle orientation phase. Such a difference is undoubtedly due to the nature of normal matched features, which are not as well defined as GCPs. The latter are always selected at locations with good contrast and matching in such areas will be more accurate.

The sign of $dZ$ discrepancies was determined by subtracting the matched DEM from the reference data-set. There are some systematic shifts of the matched DEMs against the MAP-DEM which peaked at 9.6 m, always with a negative value (see Table III). The shifts are also visible in the frequency distribution (see Fig. 8). These negative shifts confirm that the matched DEMs are higher than the MAP-DEM, and this should be the case because the MAP-DEM was measured manually by setting the floating mark down to the solid ground whilst the matched DEMs inevitably include objects located above the terrain surface.

Fig. 8. Frequency distribution of $dZ$ discrepancies obtained by the matched DEMs against the reference DEMs (left shows the open area while the right indicates the forest area; $x$ axis represents $dZ$ discrepancies, $y$ axis with the number of points).
The height discrepancies are also dependent upon the terrain inclination as can be seen in Table III. The slope-dependent component corresponds in part to the horizontal accuracy of the height points. The values for the open area are a little larger and in such areas it is expected that a greater number of buildings can influence the height discrepancies. Inside the forest area there is a lower dependency upon the slope.

**DEM Accuracy—SRTM + SAR**

A complete description of the X-band component of the SRTM is provided by the Remote Sensing Data Center (DFD) of the German Aerospace Center (DLR). The coverage of the acquired X-band data at 1 arcsec (≥30 m) spatial resolution can be accessed at DFD’s web gate, EOWEB (http://www.eoweb.dlr.de). For the C-band, 3 arcsec (≥90 m) data can be downloaded from the web at ftp://edcsgsg.cr.usgs.gov/pub/data/srtm/Eurasia, while 1 arcsec data is only freely available over the USA. In Kocak et al. (2004), the accuracies of X- and C-SAR DEMs were assessed based on the MAP-DEM and findings were quite similar to each other with the resulting rmse-Z values about 12 m. However, the reference DEM itself is not free of error; for this reason the interferometric DEMs have been compared with GPS-surveyed GCPs. The rmse-Z values obtained for X- and C-band DEMs were found to be in the range of 5-4 and 9-4 m, respectively.

However, better results are available for X- and C-band SAR DEMs. For instance, Koch et al. (2002) carried out a geometric accuracy test of DEMs from the X-band based on the reference data (trigonometric points and reference DTM) of a test site south of Hanover, Germany. The maximum height difference in this area is about 450 m. The standard deviation

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**Table III. Discrepancies between the matched DEMs and the reference DEMs.**

<table>
<thead>
<tr>
<th>DEM type</th>
<th>Area</th>
<th>Rmse-Z (m)</th>
<th>Shift (m)</th>
<th>Rmse-Z without shift (m)</th>
<th>Standard deviation of height depending upon the slope</th>
<th>Rmse-Z (m)</th>
<th>Shift (m)</th>
<th>Rmse-Z without shift (m)</th>
<th>Standard deviation of height depending upon the slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAP</td>
<td>All</td>
<td>14.35</td>
<td>-7.57</td>
<td>12.19</td>
<td>12.77 + 4.74 × tan a</td>
<td>14.64</td>
<td>-8.18</td>
<td>12.15</td>
<td>12.75 + 5.44 × tan a</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>13.14</td>
<td>-6.59</td>
<td>11.37</td>
<td>11.29 + 5.24 × tan a</td>
<td>13.24</td>
<td>-6.93</td>
<td>11.28</td>
<td>11.11 + 5.83 × tan a</td>
</tr>
<tr>
<td></td>
<td>Forest</td>
<td>15.56</td>
<td>-8.70</td>
<td>12.90</td>
<td>14.86 + 3.06 × tan a</td>
<td>15.96</td>
<td>-9.65</td>
<td>12.71</td>
<td>15.16 + 3.59 × tan a</td>
</tr>
<tr>
<td>SRTM-X</td>
<td>All</td>
<td>9.39</td>
<td>-2.87</td>
<td>8.94</td>
<td>7.26 + 6.08 × tan a</td>
<td>10.19</td>
<td>-3.01</td>
<td>9.73</td>
<td>7.98 + 6.24 × tan a</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>8.94</td>
<td>-2.85</td>
<td>8.46</td>
<td>6.92 + 5.89 × tan a</td>
<td>9.65</td>
<td>-2.70</td>
<td>9.17</td>
<td>7.52 + 6.14 × tan a</td>
</tr>
<tr>
<td></td>
<td>Forest</td>
<td>9.69</td>
<td>-2.97</td>
<td>9.26</td>
<td>7.24 + 6.92 × tan a</td>
<td>10.30</td>
<td>-3.04</td>
<td>9.94</td>
<td>7.64 + 7.49 × tan a</td>
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<tr>
<td>SRTM-C</td>
<td>All</td>
<td>13.90</td>
<td>-4.83</td>
<td>13.04</td>
<td>10.42 + 10.57 × tan a</td>
<td>13.61</td>
<td>-5.48</td>
<td>12.46</td>
<td>10.75 + 8.62 × tan a</td>
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<tr>
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<td>Open</td>
<td>13.53</td>
<td>-4.68</td>
<td>12.69</td>
<td>10.12 + 10.63 × tan a</td>
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<td>14.30</td>
<td>-5.99</td>
<td>12.98</td>
<td>11.56 + 9.01 × tan a</td>
</tr>
</tbody>
</table>
was found to be ±3·3 m in open landscape using spatial similarity transformation. Rosen et al. (2001) reported the rms height error of DEM from SRTM C-band data on the order of 3 m using six fully mosaicked cells for the NIMA test sites.

Fig. 10(a) and (b) shows the interferometric DEMs of the testfield generated by the X- and C-band SAR data from the SRTM (see Fig. 2 for coverage). Based on the height discrepancies between the matched DEMs and the X-band interferometric DEM, rmse-Z values were found to be 8·46 to 9·17 m and 9·26 to 9·94 m in open and forested areas, respectively. Trends were also quite similar for the C-band, but this time larger rmse-Z values were obtained for both area types as 12·26 to 12·69 m and 12·98 to 13·27 m. However, C-band results are more representative than those of the X-band due to the large and complete coverage of C-band over the SPOT 5 HRG Level 1A and 1B images. The dependency on slope in open and forest areas is nearly equal, but slope-dependent components are larger when compared with those resulting from the comparison with MAP-DEM.

**DEM Accuracy—GPS Profiles**

For a further validation of the DEM data, accuracy tests have been carried out using three GPS profiles measured along the main roads of the Zonguldak testfield (see Fig. 1). In total, 55 points have been collected by differential GPS and their height values were compared with those of matched DEMs. As a result, rmse-Z values were found to be 3·30 and 2·30 m for 1A and 1B generated DEMs, respectively. Fig. 11(a) and (b) shows the error vectors at profile points for each DEM, respectively.

**Discussion of Results**

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

(i) In the sensor orientation phase, with the PCI system, the rmse values with the SPOT 5 HRG Level 1A and 1B stereopairs fall into the sub-pixel range. Provided that at least six control points were used in the computation, with different GCP/ICP configurations ensuring uniform distribution of selected control points over the testfield, Level 1A and 1B imagery produced almost similar results. Such an outcome is in line with the results obtained from former SPOT 4 data-sets (see Al-Rousan and Petrie, 1998) which have also shown that the results from Level 1B images were as good as those from Level 1A imagery. For SPOT 5 HRG imagery, the results obtained also fit with those acquired by Nonin and Piccard (2003) in planimetry; however, in the Z direction they have obtained better results which were also influenced by the B/H ratio used. In Korns et al. (2004), although supermode imagery has been implemented, results are still comparable with those obtained by standard mode imagery in this test.

(ii) DEM generation was successful on the testfield which has mixed and mountainous terrain type. For matching the Level 1A and 1B stereopairs, the program yielded a correlation success rate of about 85%. Based on the correlation map supplied by the program, areas with gaps and lower correlation rates are mainly located in the forests and on ridges.

(iii) For validation of the matched DEM, it has been compared against the reference DEM based on digitised contour lines from the 1:25 000 scale topographic maps, interferometric DEMs from the SRTM X- and C-band SAR data and the GPS
profiles measured along the main roads. Although the MAP and SRTM X-band DEMs cover only a small part of the matched DEMs, their areal coverage still includes diverse characteristics to analyse the accuracy level of the generated SPOT DEMs. However, results from the SRTM C-band DEM are more representative because it covers the whole model. With regard to the accuracy, SRTM X-band DEM has revealed a better result compared with the C-band DEM because of its smaller grid size.

(iv) Another issue in validating the SPOT DEMs is the accuracy of the reference data-sets used. As stated in the previous sections, accuracies of MAP and InSAR DEMs are too similar to the generated DEMs. However, these are the only available high quality reference materials available for the country where the testfield is located. There is no more accurate DEM source such as laser scanning in the test area. Of course, this undermines the validation work made by them, but still shows what can be achieved with available data-sets for the DEM generated by medium resolution space imagery such as SPOT 5 in these conditions. This matter became more apparent when the quality of reference data-sets was compared to those used in Nonin and Piccard (2003) and Kornus et al. (2004). Reference DEMs used for validation have an accuracy of about 1 m, so here their own errors do not contribute significantly to the rmse values obtained from the analysis.

Fig. 10(a), (b). SRTM X- and C-band interferometric DEMs available for the testfield.
Comparison made by GPS profiles gave sub-pixel height accuracy for each level. This may give a biased measure of the matched DEM accuracy because profile points are all linear features located on roads where matching will be more successful.

**Conclusions**

In this study, the geometric accuracies of sensor orientation and DEM generation procedures with SPOT 5 HRG Level 1A and 1B stereo-images have been fully evaluated on the Zonguldak testfield. Both Level 1A and 1B data produced quite similar accuracy values in terms of orientation and DEM validation based on the reference data-sets. For the orientation side, rmse values of 2.5 to 3.2 m in $X$, 2.8 m in $Y$ and 3.3 to 3.5 m in $Z$ were acquired using GPS-surveyed GCPs. Different GCP/ICP configurations were tested and the PCI solution shows smooth changes in accuracy values down to where only six GCPs were used in the adjustment. Error vectors resulting from the orientation of Level 1A and 1B gave a similar error pattern with random distribution overall, but locally showing some systematic pattern. Raster DEMs were created by an automatic image correlation technique and only a small number of mismatches and gaps occurred, mainly on ridges at high altitude and with forest cover. Matched DEMs were validated against reference data-sets: MAP-DEM digitised from the 1:25 000 topographic maps, interferometric DEMs from SRTM X- and C-band data and the GPS profiles measured along the main roads of the testfield. In the validation, open and
forested areas were separated based on the image classification of the testfield using Landsat TM multispectral images. While the comparison with X-band and MAP-DEMgs produced a height accuracy of 9 to 10 m and 11 to 13 m for open and forested areas, respectively, rmse values were computed as 12 to 13 m based on the C-band DEM. The latter value was more representative since C-band DEM totally covers the imaged area. Finally, GPS profiles measured along the main roads of the testfield produced rmse-Z values of 3.30 and 2.30 m for 1A and 1B DEMs, respectively.

ACKNOWLEDGEMENTS

This work was carried out under the international project supported by TUBITAK (Turkey)–JULICH (Germany) cooperation with code No. 101Y090.

REFERENCES


Résumé

On a étudié des images stéréo de niveau 1A et 1B de SPOT 5 HRG prises sur le polygone d’essai de Zonguldak au Nord-Ouest de la Turquie. Il s’agit d’images gauche et droite présentant un rapport base sur altitude de 0.54. La tache (l’équivalent du pixel au sol) est de 5 m. On a effectué l’orientation des faisceaux avec le jeu de logiciels PCI Geomatica V9.1.4 et obtenu des précisions subpixellaires sur la localisation en 3D, à condition d’utiliser au moins 6 points d’appui dans les calculs. Les erreurs moyennes quadratiques et les vecteurs résidus du niveau 1A sont les mêmes que pour le niveau 1B, et cela même pour différentes configurations des points d’appui et de vérification. On a ensuite dérivé des niveaux 1A et 1B des MNA (Modèles Numériques des Altitudes) sur le polygone d’essai par appariement automatique d’images. On a validé ces MNA par un MNA de référence issu des cartes topographiques au 1:25 000 par numérisation, par des MNA interférométriques provenant des données du radar à synthèse d’ouverture à bandes C et X SRTM, et par des profils GPS sur les routes principales de ce polygone. Ces jeux de données sont les seules données de référence de bonne qualité disponibles sur cette zone, bien que leur défaut soit de présenter des précisions tout à fait comparables à celles des MNA issus de SPOT. La précision altimétrique sub-pixelaire indiquée provient des comparaisons avec les points des profils. Encore faut-il ajouter qu’il s’agit de points où l’appariement d’images est réussi, c’est-à-dire lorsque les conditions sont favorables, ce qui peut biaiser dans une certaine mesure la valeur de la précision obtenue sur les MNA correspondants.

Zusammenfassung

Es werden Stereoaufnahmen aus zwei SPOT 5 HRG Produkten, dem Level 1A und dem Level 1B analysiert. Die Stereoaufnahmen decken das Zonguldak Testfeld im Nordwesten der Türkei ab. Die Stereobildpaare besitzen ein Basis-Höhenverhältnis von 0.54. Die Pixelgröße am Boden ist 5 m. Die Bündelausgleichung wurde mit dem Softwarepaket PCI Geomatica V9.1.4 durchgeführt. Damit waren Subpixelgenauigkeiten in der 3D Geopositionierung erreichbar, vorausgesetzt, dass mindestens sechs Passpunkte in der Ausgleichung verwendet wurden. Die mittleren quadratischen Fehler und die Vektoren der Verbesserungen sind für die beiden untersuchten Produkte gleich, auch für den Fall unterschiedlicher Passpunkts- und Kontrollpunktkonfigurationen. Auf der Basis der ermittelten Orientierungen wurden für die Daten aus Level 1A und Level 1B je ein Digitales Höhenmodell des Testfeldes mit Hilfe von automatischer Bildzuordnung bestimmt. Die Digitalen Höhenmodelle wurden mit
verschiedenen Vergleichsdaten validiert: erstens mit einem Referenzhöhenmodell, das aus einer Digitalisierung einer topographischen Karte im Maßstab 1:25 000 stammt, zweitens mit einem Höhenmodell, das aus interferometrischen Messungen mit SRTM SAR Daten (X- und C-Band) stammt und drittens mit GPS Profilen, die entlang der Hauptverkehrsstraßen im Testfeld erfasst wurden. Obwohl die Genauigkeiten der Referenzdaten im Bereich der generierten Höhenmodelle aus den SPOT Daten liegen, mussten sie verwendet werden, da sonst kein genaueres Vergleichsmaterial zur Verfügung stand. Der Vergleich mit Punkten aus den GPS Profilen lässt eine Höhengenauigkeit im Subpixelbereich vermuten. Allerdings liegen die gemessenen Profile in Gebieten mit guter Textur in der die Bildzuordnung in allen Fällen erfolgreich war. Somit ist obige Aussage zur Genauigkeit, die darauf aufbaut, sicherlich nicht allgemeingültig.

Resumen

En este estudio se han analizado varias escenas estereoscópicas HRG del satélite SPOT 5 de niveles 1A y 1B que cubren el campo de ensayo Zonguldak, en el noroeste de Turquía. Las escenas estereoscópicas se componen de las imágenes izquierda y derecha con una razón base-altura de 0.54 y un tamaño de pixel de 5 m. Se ha llevado a cabo la orientación por haces con el programa PCI Geomatica V9.1.4 obteniéndose en cada eje unas exactitudes subpixel en la geoposición 3D, siempre que en el cálculo se utilizasen al menos 6 puntos de control. Los valores de error RMS y los vectores de los errores residuales obtenidos para los niveles 1A y 1B son similares, incluso utilizando distintas configuraciones de puntos de campo y de validación. Conocida la orientación de la escena, se calcularon mediante correlación automática diferentes Modelos Digitales de Elevación (MDE) del campo de ensayo para los niveles 1A y 1B, que se validaron con el MDE de referencia obtenido a partir de la digitalización de los mapas topográficos a escala 1:25 000, del MDE obtenido por interferometría radar de las bandas X y C del SRTM y de los perfiles GPS obtenidos a lo largo de las principales vías de comunicación del campo de ensayo. Aunque las exactitudes de los datos de referencia son muy similares a las de los MDE calculados con las imágenes SPOT, éstas son las únicas fuentes de referencia de calidad alta disponibles en esta área. La exactitud subpixel en altimetria fue obtenida comparando los valores con los puntos del perfil. Sin embargo, dichos puntos están localizados en lugares favorables en donde la correlación es siempre buena, por lo que este resultado puede dar una medida sesgada de la exactitud de los respectivos MDE.