Quality checking of DEM derived from satellite data (SPOT and SRTM)

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ABSTRACT: The widespread availability of good quality digital elevation data opens the door to systematic and improved automation of orthoimage production, in the context of the Common Agricultural Policy and the checks on aid applications with remote sensing activity. Best practice for production of VHR (<1 m pixel) imagery meeting these requirements usually states a quality of 5 m RMSE in Z is required.

During 2004, two sources have emerged: the "open source" SRTM C-band (3 arc second, approx. 90 m grid size) data, released to the general public via the internet and requiring careful processing, and SPOT Image’s commercial Reference 3D® product, which is created using the stereo HRV sensor on the SPOT5 platform. Both data sources have official general specifications somewhat lower than the 5 m RMSEZ, but given the usually limited relief in agricultural areas, an investigation into the quality of these dataset was considered an important task.

This paper will report on the test carried out by the FOMI and JRC to determine the suitability of the SPOT Image Reference 3D® and Shuttle Radar Topography Mission (SRTM) products for use in production-process ortho-rectification of satellite imagery. The theoretical geometric accuracy of the InSAR data like SRTM (Balmer, 1997) or of more conventional optical correlation (Buyuksalih, 2004) is already partially documented; that of the Reference 3D product is less well recorded. Many of these tests correspond to specific localised comparisons, and results are difficult to generalise; nevertheless the availability of such
data open the door to important, continental scale use in operational applications, if the issue of data quality determination can be addressed.

An example of an application requiring a standard, operational product is the verification of agricultural subsidies in the regulatory context of the European Union Common Agricultural Policy (CAP). In this application, very high resolution (1m ground sampling distance or smaller) imagery are used to determine the area and land-cover of agricultural parcels claimed by farmers for subsidy. For this purpose, a geometric accuracy of better than 2.5 m RMSE\(_{1D}\) (Root Mean Square Error in one dimension, either X, Y) is necessary, in accordance with the guidelines proposed by European Commission (Kay et al. 2003, Kay 2005). Such accuracy is generally only attainable by orthorectifying with a suitable digital elevation model (DEM). Through the ten years of this operational programme, experience has shown that best practices tend to impose a minimum data quality of 5 m RMSE\(_Z\) (i.e., vertical linear error) for use with the typical off-nadir collection mode of the imagery used (incidence angles of up to 30°).

Chmiel et al. (2004) showed, in an EU-wide assessment of very high resolution image orthorectification on 34 agricultural sites, that a dominant constraint on successful processing was DEM quality; many sites in Europe still do not have readily available suitable data. However, in 2004, two sources emerged as potential solutions:

- the “open source” SRTM C-band (3 arc second spacing, approx. 90 m) data, released to the general public via the internet and requiring careful processing,
- and SPOT Image’s commercial Reference 3D® product, which is created using the stereo HRS sensor on the SPOT5 platform.

Both data sources have official general specifications somewhat lower than the 5 m RMSE\(_Z\), but given the usually limited relief in agricultural areas, an investigation into the quality of these dataset was considered an important task.

A collaboration agreement was made between SPOT Image, the JRC and FÖMI to carry out the study, using a large test site located in an agricultural region in Hungary.

2 DATASETS AND STUDY SITE

2.1 The Reference 3D product

The Reference 3D product is a uniform grid of terrain elevation values and is obtained through automatic correlation of SPOT HRS stereo-pairs (SPOT IMAGE, 2005). The tile, subject for this study, was produced within a block of 14 stereo-strips. Bundle block adjustment was performed only using vertical control points (so called 0-level points) of which 16 points where on coastlines in the block (i.e. at great distance from the study site itself). The test site data were delivered with a pixel size of 1 arc second for the DEM (approx 20 m \(\times\) 28 m for the scene tested); the raster grid was made up of 3601 \(\times\) 3601 cells (nearly 13M data values). The Reference 3D accuracy specification statement is quoted at the 90% confidence level, in terms of linear error relative to the EGM 96 geoid, and is 10 m for slopes below 20%, 18 m for slopes between 20% and 40%, and 30 m for slopes above 40%; we interpret that this corresponds to an RMSE\(_Z\) of \(\sim\) 7 m in a typical case.

Two regions in the delivered DEM – a first for which the source imagery where cloud covered, a second of marshland – representing 5.32% of the tile were created using SRTM data (90 m resolution) since the autocorrelation process was unsuccessful (Bernard, pers. comm.).

The product also includes information on correlation quality, and an orthoimage derived from the HRS instrument (the source data also for the DEM product). The sample orthoimage product tested was delivered as a geographic tile of 1° by 1° aligned along parallels and meridians, and with a pixel size of 1/6th arc seconds (approx 5 m \(\times\) 3 m for the scene under test). The stated geometric accuracy is circular error (i.e., two dimensional linear statement) of 16m at the 90% confidence level, corresponding again to around RMSE\(_{1D}\) of \(\sim\)7 m.
2.2 **SRTM product**

The Shuttle Radar Topography Mission (SRTM) is a joint project between NASA and NGA (National Geospatial-Intelligence Agency) to map the world in three dimensions. SRTM utilised dual Spaceborne Imaging Radar (SIR-C) and dual X-band Synthetic Aperture Radar (X-SAR) configured as a baseline interferometer, acquiring two images at the same time. These images, when combined, can produce a single 3-D image (Bamler, 1997). Flown aboard the NASA Space Shuttle Endeavour February 11-22, 2000, SRTM successfully collected data over 80% of the Earth’s land surface, for most of the area between 60°N and 56°S latitude (USGS, 2005).

SRTM data has been used to generate a digital topographic map of the Earth’s land surface with data points spaced every 3 arc second for global coverage of latitude and longitude (approximately 90 meters). The absolute horizontal and vertical accuracy is 20 meters (circular error at 90% confidence) and 16 meters (linear error at 90% confidence), respectively (USGS, 2005).

2.3 **Study site**

The region chosen for the test was located south of the Hungarian capital Budapest, covering typical moderate relief, agriculture and forest land use; the Reference 3D product being delivered as a 1° tile, an area between the 18°E and 19°E meridians and 46°N and 47°N parallels was selected (Figure 1). The area is just less than 13,000 km²; maximum altitude of the terrain is 678 m, with the hilliest region being north of the city of Pecs. The Danube River flows to the South of the site from Budapest.

![Figure 1. Location of the study site](image)

The region chosen represents a typical productive agricultural landscape, with moderate relief.

3 **STUDY METHODOLOGY**

The test methodology relied upon the existence of high quality reference data covering the entire site. Through FÖMI, it was possible to access data of an assured level of quality (Winkler, 2004); the reported RMSE$_Z$ value (calculated using more then 55,000 points) of the benchmark digital
elevation data used in the comparison is 70 cm, i.e. an order of magnitude improvement compared to the specification of either Reference 3D or SRTM data.

The benchmarking depended upon two types of reference data (Winkler, 2004):

– Existing large scale mapping data (ortho-photos, DEM, GCPs) available in Hungary
– The trigonometric points from the 4th order network

3.1 Land cover stratification

An analysis of the Corine Landcover CLC 2000 map – produced in line with the Corine Land Cover programme – from FOMI was made to produce three broad land cover categories (Urban, Agriculture, Forest) over the test site (Table 1).

Table 1. Land cover categorisation using CLC 2000 codes

<table>
<thead>
<tr>
<th>Urban classes</th>
<th>Agricultural classes</th>
<th>Forest classes</th>
<th>Water classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CODE class name</td>
<td>CODE class name</td>
<td>CODE class name</td>
<td>CODE class name</td>
</tr>
<tr>
<td>111</td>
<td>Continuous urban fabric</td>
<td>211</td>
<td>Non-irrigated arable land</td>
</tr>
<tr>
<td>112</td>
<td>Discontinuous urban fabric</td>
<td>221</td>
<td>Vineyards</td>
</tr>
<tr>
<td>121</td>
<td>Industrial or commercial units</td>
<td>222</td>
<td>Fruit trees and berry plantations</td>
</tr>
<tr>
<td>122</td>
<td>Road and rail network</td>
<td>231</td>
<td>Pastures</td>
</tr>
<tr>
<td>124</td>
<td>Airports</td>
<td>242</td>
<td>Complex cultivation patterns</td>
</tr>
<tr>
<td>131</td>
<td>Mineral extraction sites</td>
<td>243</td>
<td>Agriculture with natural vegetation</td>
</tr>
<tr>
<td>132</td>
<td>Dump sites</td>
<td>321</td>
<td>Natural grasslands</td>
</tr>
<tr>
<td>141</td>
<td>Green urban areas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>142</td>
<td>Sport and leisure facilities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>411</td>
<td>Inland marshes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The three grouped categorisations corresponded to 5% of the test area (Urban), 75% of the test area (Agricultural), and 20% of the test area (Forest). The water class was insignificant; in any case, areas corresponding to this class were excluded from the test.

As a further means of stratifying land cover, an elevation slope mask was made from the Reference 3D image. This slope-mask was classed into 4 levels: between 0% and 10%, 10%–20%, 20%–40%, and more than 40%, corresponding with the stated performance classification by SPOT Image.

3.2 Reference 3D HRS Orthoimage quality check

The orthoimage was tested according to the general guidelines of the JRC (Kay, 2005), namely exterior control using independently acquired check points. The reference data is the MADOP ortho-rectified imagery with stated geometric accuracy equal to +/-60 cm in x and y.

The JRC guidelines are intended for batch processing of somewhat smaller (10 × 10 km up to 60 × 60 km) orthoimages. However, they can be adapted to the Reference 3D HRS orthoimage quite easily, and due to the widespread availability of high quality check points (Winkler, 2004), a set of 200 well defined points was identified and used in the test.
3.3 Methods and procedures for SRTM and Reference 3D performance measurement

With two datasets in raster format, it at first seems obvious to make a direct comparison by the superimposition of the equivalent samples. However, a number of factors complicate this procedure: different raster cell sizes, vertical datums, projections to name the principle complicating factors. Whilst these issues can all be addressed – through relatively sophisticated GIS processing – the potential loss of information during the re-sampling has to be taken into account. After comparing several approaches below, we propose an approach based upon the conversion of the raster SRTM data into a ‘point vector’ data, which is then compared with points derived from the reference DEM.

3.3.1 Absolute accuracy determination on the basis of the GPS check points
The test raster (SRTM or Reference 3D) data was superimposed with the set of approximately 5,000 check points and the elevation derived from the test raster using bilinear interpolation. On the basis of the differences between the calculated Z-coordinates derived from test data and the check points, the RMSE, standard deviation and mean values are calculated. In addition, analogous analysis was performed on the national DEM raster data (used in the tests below) to ensure homogeneity of results.

3.3.2 'Raster to raster' method
The ‘raster to raster’ (R2R) method directly compares two raster data sets, namely: reference national DEM and the SRTM or Reference 3D raster data by superimposing equivalent raster matrices. Common pixel size, projection system and matrix size (number of rows and columns) are the necessary conditions for comparing two data sets; therefore, at the start, the reference data was re-projected to each test product system, and a nearest neighbour approach used to avoid generating new sample values for the reference dataset. The overlay resulted in values that quantify the difference between the two data sets with height differences calculated for every pixel. For these differences RMS, standard deviation and mean values are calculated.

The main advantage of the R2R method is that the value of every individual pixel is analyzed and the analysis covers the complete test area; nevertheless, the lack of the interpolation during the elevation determination process is a potential weakness of this method.

3.3.3 'Raster to vector' method
The second applied method is called ‘raster to vector’ (R2V). Again, it deals with the superimposition of the SRTM or Reference 3D grid and the reference DEM data. In the preliminary stage, the test raster data has to be converted into an ASCII co-ordinate pairs file to be imported as a vector layer of regularly distributed points (grid vertexes). These vectors are then transformed into the particular national reference system. Then, it is possible to superimpose the two data sets and determine the elevation of every test grid vertex on the base of the reference raster layer. The standard deviation and mean values of the elevation’s differences (between the original DEM point and the corresponding vertex) are calculated for the quality control purposes. The major benefit of the R2V method is that the points’ density and distribution is the same for every test area; however, it still does not include interpolation during the elevation determination process.

3.3.4 'Raster to vector' method with bilinear interpolation
The third method (R2VB) is similar to R2V as it also deals with the comparison of two data sets by superimposition of the test grid and reference DEM, and the determination of every grid vertex elevation from the reference raster. However, the process of the elevation determination now includes a bilinear interpolation algorithm instead of the simple nearest neighbour sampling.

The main advantages of the R2VB method are:

- Fixed point density and distribution for every test area,
- Elevation determination by bilinear interpolation between 4 neighbouring pixels.
4 RESULTS

4.1 Reference3D

The Reference3D product has a predictable performance (Table 2, Figure 2), working better on terrain that is of lower slope angles and in general following the optical surface of the object under view. This corresponds well with the official specification of the product.

For example, in areas of agricultural land of low slope (<20%) the product performs consistently (3.03 m RMSE$_Z$) inside the expected requirements for EU Common Agricultural Policy orthoimage production for checking farmers with VHR satellite data. Even on steeper slopes, the data could be considered – for this land cover category – as generally being of acceptable quality.

For the other two land cover classes, the results are partially satisfactory. Urban classes show more variability (RMSE$_Z$ generally over 5 m) but the area checked is marginal in the test site. Forest areas presented a more significant part of the dataset, and the product typically shows a mean value suggesting that the top of tree canopies is the reference point for the Digital Surface Model.

The HRS orthoimage product also performed well inside the stated product accuracy, with a RMSE$_X$ of 2.64 m, and RMSE$_Y$ of 5.09 m, although the mean values appear slightly shifted with a mean Y value of −4.10 m.

4.2 SRTM

The SRTM product – like the Reference 3D – has a predictable performance in the site tested, working better on terrain that is of lower slope angles (Table 3, Figure 3). Again, the result corresponds favourably with the official product specification and other reports.

Like Reference 3D, SRTM performs well in areas of agricultural land cover with low slope (<20%). The results –2.64 m RMSE$_Z$ – are well inside the requirements for operational orthoimage production, and even marginally better than the Reference 3D tile tested.

For the other two broad classes (urban and forest areas), the results are partially satisfactory. Urban classes show more better results (below 4 m RMSE) than for Reference 3D, but Forest areas presented a significant decrease in performance, again in line with typical reports of SRTM results, with a RMSE$_Z$ generally under 10 m.

5 CONCLUSIONS

The results show that, for the tile tested, both products performed better than their standard specification, with consistent behaviour for the generalised land classes in the site (agricultural land, urban zones, forest areas) and the slope categories. On this basis, it was concluded that both products are useful alternatives or even primary sources for operational programmes, and in particular suitable for rectification of most VHR imagery in the context of the EU programmes without further processing, besides projection/datum transformations.

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Figure 2. Reference 3D result summary.

Table 2. Reference 3D Results by land class and slope category

<table>
<thead>
<tr>
<th>Forest</th>
<th>Slope, %</th>
<th>RMSE, (m)</th>
<th>No. of pixels</th>
<th>%</th>
<th></th>
<th>Arable</th>
<th>Slope, %</th>
<th>RMSE, (m)</th>
<th>No. of pixels</th>
<th>%</th>
<th></th>
<th>Urban</th>
<th>Slope, %</th>
<th>RMSE, (m)</th>
<th>No. of pixels</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>4.74</td>
<td>1433913</td>
<td>55.9%</td>
<td></td>
<td>&lt;10</td>
<td>2.65</td>
<td>8462994</td>
<td>90.1%</td>
<td></td>
<td>&lt;10</td>
<td>3.22</td>
<td>558595</td>
<td>91.0%</td>
<td></td>
<td></td>
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<tr>
<td>10–20</td>
<td>5.23</td>
<td>660224</td>
<td>25.7%</td>
<td></td>
<td>10–20</td>
<td>3.03</td>
<td>759905</td>
<td>8.1%</td>
<td></td>
<td>10–20</td>
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<td>45642</td>
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<tr>
<td>20–40</td>
<td>5.98</td>
<td>446315</td>
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<td>20–40</td>
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<td>165457</td>
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<td>5.78</td>
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<tr>
<td>&gt; 40</td>
<td>7.28</td>
<td>24037</td>
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<td>2724</td>
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<td>&gt; 40</td>
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<td>223</td>
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<td>Total</td>
<td>613728</td>
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</tbody>
</table>
Table 3. SRTM Results by land class and slope category

<table>
<thead>
<tr>
<th>Slope, %</th>
<th>RMSE_x (m)</th>
<th>No. of pixels</th>
<th>%</th>
<th>Slope, %</th>
<th>RMSE_x (m)</th>
<th>No. of pixels</th>
<th>%</th>
<th>Slope, %</th>
<th>RMSE_x (m)</th>
<th>No. of pixels</th>
<th>%</th>
</tr>
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<tbody>
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<td>&lt;10</td>
<td>6.22</td>
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<td>55.9%</td>
<td>&lt;10</td>
<td>1.91</td>
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<td>&lt;10</td>
<td>1.89</td>
<td>62044</td>
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<tr>
<td>10–20</td>
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<td>25.7%</td>
<td>10–20</td>
<td>2.64</td>
<td>84234</td>
<td>8.1%</td>
<td>10–20</td>
<td>3.11</td>
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</tr>
<tr>
<td>20–40</td>
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<td>17.4%</td>
<td>20–40</td>
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<td>18459</td>
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<td>3.98</td>
<td>1015</td>
<td>1.5%</td>
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<td>12.06</td>
<td>2697</td>
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<td>4.08</td>
<td>298</td>
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<td>&gt; 40</td>
<td>8.28</td>
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<tr>
<td></td>
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<td>1043517</td>
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<td>68169</td>
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Figure 3. SRTM result summary.
REFERENCES


