# COMPARISON OF DIGITAL ELEVATION DATA FROM AIRBORNE LASER AND INTERFEROMETRIC SAR SYSTEMS

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## ABSTRACT

Requirements for precise digital elevation data (i.e., Digital Elevation Models, or DEMs) of varying levels of detail are being formulated for different fields of application. The degree of detail found in a DEM is usually characterized by the horizontal sample spacing and by the vertical accuracy of the samples. Increased detail is normally associated with increased cost to the user, which fuels the debate over which technologies are suitable for which applications. In this paper, we present the results of comparative tests of two technologies from which are derived relatively detailed digital elevation data sets with sample spacings of a few meters. The two elevation data sets have been compared for a section of variable terrain in southern Germany, approx. 10 km by 20 km in size. The data sets were produced by an airborne laser scanner and an airborne interferometric SAR sensor, respectively. The laser scanner data set consisted of two coordinated list sets of elevation measurements with a variable ground spacing ranging from approx. 1 m to 10 m. One list set contained measurement points of the earth's surface, whereas the second list set held measurement points of the vegetation surface. The interferometric SAR data set consisted of elevation data in a regular grid with a sample spacing of 5 m. Using somewhat different approaches, the laser and radar data sets were assessed independently at the University of Karlsruhe and at Intermap Technologies, Corp. in Calgary, Canada. Three different comparative methods were applied to evaluate the elevation data sets. All comparisons came to similar results, namely, that both elevation data sets are in good agreement for bare soil or areas of low vegetation coverage (less than 0.5 m elevation difference), whereas larger elevation differences were found for all areas of substantial vegetation coverage as well as for settlement areas.

## 1 INTRODUCTION

A wide range of applications is now driving the requirements for increased detail in Digital Elevation Models (DEM). Detail in this instance is defined by the horizontal sample spacing and vertical accuracy of the measurement. Traditionally, DEMs have been produced by survey methods or by stereo photogrammetry. In this paper, we restrict ourselves to a comparison of DEMs from two active sensors, airborne scanning laser and airborne interferometric SAR (Synthetic Aperture Radar), which are capable of providing elevation samples every few meters and with sub-meter vertical accuracy. Focusing on this level of detail precludes inclusion of DEMs created from repeat-pass satellite SAR technology, as well as those from the recent NASA/DLR/ASI SRTM mission. The airborne laser scanner approach has been described in various papers, e.g. (Lohr 1999) or (Wever 1999) for the basics and (Kraus 1999, Knabenschuh 1999, von Hansen 1999) for applications. Several airborne interferometric SAR systems are currently in use. The interferometric process has been widely discussed in the literature, particularly for the case of repeat pass interferometry, e.g. (Zebker 1992), while some general issues associated with airborne interferometry have been discussed in (Gray 1993).

Analysis of the accuracy of elevation measurements is often performed on the basis of a number of control points, the absolute coordinates of which can be determined very precisely using GPS techniques, refer to (Kleusberg 1999). While very relevant, this approach limits the ability to differentiate the effects associated with the fine spatial detail provided by the sensors considered here. In particular, it is difficult or impossible, using control points alone, to assess the accuracy of large area elevation measurements of regions with relief and various vegetation coverage. In this study, the laser-derived bald-earth DEM was assumed to represent 'truth' at the 15 cm to 30 cm accuracy level; the assumption was confirmed in part by (Kürbis 1998). It was therefore possible to compare the Radar DEM directly with this detailed, but wide-area, form of truth. Moreover, because aerial imagery and topographic maps were also obtained for the test area in Kraichgau (western part of Baden-Württemberg), the elevation differences could be assessed between the measurement sets in distinct areas of various relief or vegetation coverage such as urban areas, forests, water bodies, vineyards, bare soil areas, etc. In the following, DTM (Digital Terrain Model) is often used to denote the bald-earth DEM from which all surface vegetation and objects have been removed, while DSM (Digital Surface Model) references the scattering surface, including vegetation and surface objects.

## 2 BACKGROUND TO THE PROJECT

In July, 1998, Intermap Technologies collected DEM and image data of the whole of the state of Baden-Württemberg (approx. 43,000 $km^2$) using its STAR-3i airborne interferometric SAR system. A laser-derived DTM (Digital Terrain Model) for a test section of the state (approx. 150 $km^2$) had been collected on behalf of the State Mapping Agency (LVA) in Jan., 1996, by the TOPSCAN company. As a result of a data swap between Intermap and LVA, the two sets of analyses were performed independently by the University of Karlsruhe and by Intermap Technologies in Calgary. As discussed below, the objectives and approaches were somewhat different but the results and conclusions were almost identical. The main objective from the Intermap point of view was to demonstrate the absolute and relative vertical accuracies of the STAR-3i DSM in 'bald-earth' regions of the test area. The Karlsruhe university objective additionally included the assessment of vegetated and other classes of terrain, which in this comparative analysis, describes only indirectly the accuracies of the elevation measurement, but rather the response of the radar to vegetative classes.

## 3 INPUT DATA DESCRIPTION

The two prime data sets were those acquired by airborne scanning laser (an Optech scanning laser operated by TOPSCAN) and by the STAR-3i interferometric airborne SAR (operated by Intermap). Some of the comparative operational characteristics of the two systems are described in (Mercer 1999). The TOPSCAN airborne laser campaign generated an irregular elevation data set with an average point spacing of approx. 4 m. The measurement points were geoid-referenced and projected into the Gauss-Krüger system. Multiple, overlapping flight paths yielded locally variable point density. The elevation data set was partitioned by Topscan into two disjunctive subsets. One subset, containing most of the data, was to represent the elevation of the ground surface (DTM, named 'ground' in the following) and the other subset was to represent the elevation of the top level of vegetation coverage (DSM, named 'vegetation' in the following). A detailed functionality of the selection method is not known. Hence, it is uncertain to which subset the measurement points e.g. on roofs of buildings have been allocated. The laser scanner data acquisition took place on Jan. 12 and 13, 1996, during the leaf-off and agriculturally dormant season.

A second measurement campaign by the Intermap STAR-3i airborne interferometric SAR system generated a regular raster DEM with an element size of 5 m x 5 m. Radar image data were simultaneously collected and ortho-rectified during the processing activity. The data set was referenced horizontally and vertically to WGS-84 and projected into the UTM coordinate system. Data acquisition took place during the first half of July, 1998, during the leaf-on season and with crops well developed. In addition to the elevation data sets described above, panchromatic digital orthophotos of the test area with a ground resolution of 0.5 m, were obtained and used in the Karlsruhe analysis. The aerial imagery for generating these orthophotos was acquired on June 10, 1998. The determination of vegetation coverage for the various test fields was based on this date. It should be noted that the time difference between both elevation data acquisitions, and in particular the differing seasons, might influence the statistical evaluation of the elevation difference calculations unfavorably.

## 4 ELEVATION ACCURACY ASSESSMENT

The assessment of elevation differences between both, the laser scanner and the interferometric SAR data set was based on comparisons, the basis of the comparative study. Elevation differences were calculated (1) between the 'original' measurements at nearly co-located positions and (2) between co-located elevation rasters which were derived by interpolation from the 'original' measurements. The differences were calculated for both, the ground and the vegetation data subset. Several features distinguish airborne radar from laser systems, and some of these are elaborated in (Mercer 1999). For purposes of this paper, two important distinctions should be noted: (1) Each radar elevation sample is an integrated response from an approx. 5 m by 5 m cell. For a homogeneous target over the cell area, the height is representative of the geometric center of the cell. On the other hand, the laser 'footprint' is about 20 cm in diameter, with a mean spacing between the irregularly spaced point samples of about 4 m. Therefore, the laser-derived DTM is an interpolated surface, and some inter-sample detail may be lost. (2) Some fractions of the laser pulses penetrate through forest canopy to the ground, particularly in the leaf-off condition, and these were used to create the assumed bald-earth 'truth'. Conversely, the radar only penetrates, depending on radar wave length and other parameters, partially into vegetation and the derived elevation represents the effects of volumetric scattering within the canopy. The effective scattering height is dependent on system and vegetation parameters. Comparison of the radar DEM/DSM with the laser derived bald-earth DEM/DTM in forested or crop-covered areas will, therefore, provide also information about the target response to the radar.

### 4.1 Transformation Issues

Before data from the two sets could be directly compared, it was necessary to have them in a common reference system. The laser data were in a local state plane system (Bessel ellipsoid, DHDN datum, Gauss-Krger projection, Denker geoid). The radar data were in a global system (WGS-84 ellipsoidally referenced, UTM projection). The Karlsruhe approach was to transform the radar data to the local system, and this was performed by colleagues at the Fachhochschule Karlsruhe. The Intermap preference was to transform the laser data into the radar reference system. In-house software was developed by Intermap that utilized the transformation parameters provided by LVA.

### 4.2 Comparison of 'Original' Measurement Data in Karlsruhe

The comparison of 'original' measurement data was done by the authors in Karlsruhe. The method was based upon selection of laser measurement points within a limited x-y-distance from radar cell centers. Elevation differences were calculated between both, the laser and the radar data sets for those point pairs. A distance threshold of approx. 0.6 m was chosen; a smaller distance limit threshold led to selection of very small numbers of point pairs, which would not produce reliable statistical figures. For the 46 test areas of different relief and vegetation coverage, all sets of less than 20 point pairs were deleted as statistically unreliable. In the case of steep slopes or vertical break lines, elevation values taken at points which were selected through this method will differ substantially; these effects were taken into account by deleting evident statistical outliers.

### 4.3 Comparison of Co-located Elevation Rasters

The second method was to compare rasterized grid data. The Karlsruhe University and Intermap approaches were similar.

**4.3.1 Areas of Pre-selected Land Cover Type (Karlsruhe)** The authors from Karlsruhe chose a grid spacing of 4.5 m, intermediate between the 5 m spacing of the regular radar grid and the average 4 m spacing of the irregularly spaced laser data set. Both data sets were interpolated using the ARC/INFO IDW (inverse distance weighting) function with parameters set at n = 8 neighboring points, and exponent exp = 3 for the distance weighting. The approach here was to classify the test area into six sub-classes (urban, forest, water, vineyards, farmland with no or very low ground cover, farmland with vegetation), based upon interpretation of the digital ortho-photos (0.5 m resolution) and a 1 : 50.000 topographic map of the area. Polygons were digitized with respect to homogenous classes as visually interpreted. Statistical tests were performed on the elevation difference grids (radar minus laser) with respect to each of the classes. All interpolated elevation rasters for test areas which were based on too small a number of 'original' measurement points were deleted. This - evidently - refers to all test areas of the class 'water' and class 'agriculuture' and to some test areas of class 'vineyard' where the data subsets 'vegetation' of the laser scanner generated measurements were empty. This is presumably due to the mid-winter acquisition date for the laser data.

**4.3.2 Areas of Post-selected Land Cover Type (Intermap)** The Intermap method was to grid the laser points into 5 m cells matching the radar grid. In this case, the MapInfo/Vertical Mapper software package was used. An inverse distance weighting interpolator was used, with a search radius of 15 m and a weighting exponent of 2. The radar data comprised both the radar DEM and the ortho-rectified radar image (ORI) that was produced simultaneously with the DEM. The 2.5 m spacial resolution of the ORI is useful for interpretation support. An overview of the test area is presented in Fig. 4a. The test region contains a mixture of rolling hills, broad valleys, agricultural land (crops and grassland), forests, villages and infrastructure.

Because the principle thrust in this work was to observe the error magnitude of the radar DSM (relative to the laser), it was necessary to eliminate the effects of terrain coverage differences from the statistical analysis. This was done through the process of classifying and sampling sub-areas that were believed to be representative of the bald-earth. The classification was performed visually and was based on a combination of DSM, ORI and elevation difference surface. It was easy to eliminate forests, villages and other significant objects from the sample. The challenge lay in differentiating elevated crops from bare earth and low-lying crops. This cannot be done merely from inspection of the ORI, because some low-lying crops (e.g., cabbage) have bright radar returns and therefore show up well in the ORI, but are only a few centimeters above the ground. Fortunately, the crop patterns for elevated crops were quite visible in the difference surface visualization. Therefore, the bald-earth classification consisted of visually searching for the lowest (height-wise) local field patterns in the difference surface, subject to minimum areal size constraints. A total of 67 'bald-earth' sections were selected in this manner, with an average area of about 5 hectars. This sampling method will tend to over-estimate errors because of failure to remove all low-lying crop effects. The spatial distribution, although not uniform, was adequate to ensure at least one sample per $km^2$. In order to obtain a global result, the difference values from the 67 sections were analysed.

## 5 RESULTS

### 5.1 Results Comparing 'Original' Elevation Measurements (Karlsruhe)

Fig. 1 shows a graphical representation of elevation differences derived from the selected coincident point pairs of the SAR and the laser 'ground' data sets. In total, 19.390 point pairs from all 46 test areas were included in this calculation of

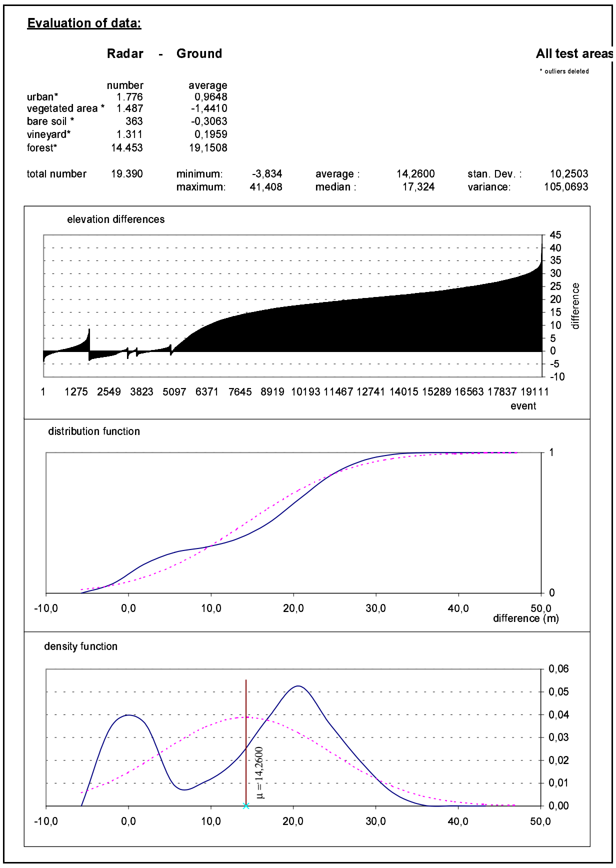


Figure 1: ’Original elevation measurements’: statistics of elevation differences selected for **’SAR - Ground’**

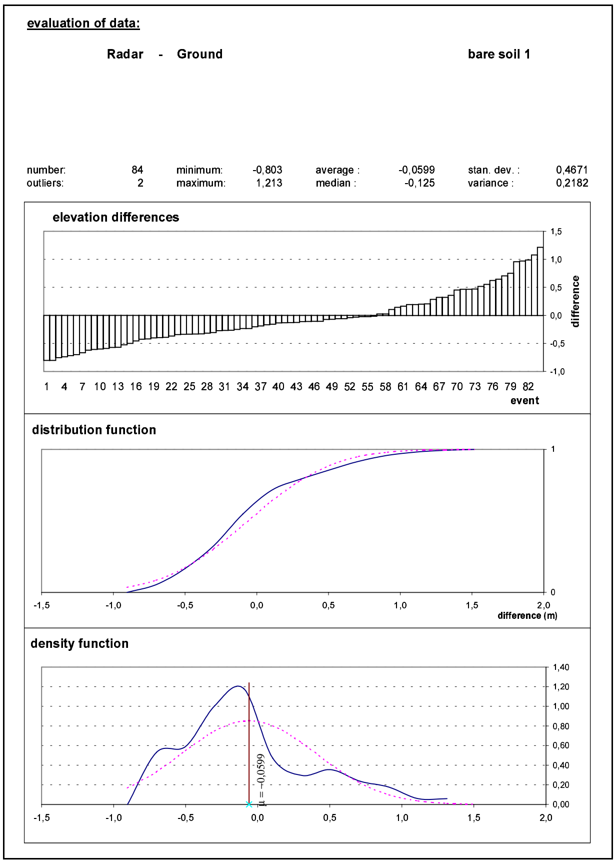


Figure 2: ’Original elevation measurements’: statistics of test area 1 (class ’agriculture, bare soil’)

elevation differences; evident statstical outliers have already been deleted. A positive difference signifies that the elevation measured by the SAR system was greater than the elevation measured by the laser scanner. The overall average amounts to +14.26 m with a standard deviation of 10.25 m. For the different land cover types included, the respective number of point pairs and the average value of the elevation differences are given. The histogramm of the differences conveys that the statistical values are dominated by the large number of positive differences in point pairs for the class ’forested areas’. The density function of the elevation differences indicates that a minority of differences (belonging to classes ’urban’, ’agriculture’, ’vineyard’, and ’water’) accumulates in the 0 m range, whereas a majority of differences (belonging to the class ’forest’) accumulates in the +20 m range. A theoretical gaussian distribution is overlayed as a dotted line. A graphical representation of the elevation difference statistics of a single test area of the class ’agriculture, bare soil’ is shown in Fig. 2. A total of 84 point pairs were selected from the SAR and and the laser ’ground’ data sets. The difference values cover the range between -0.8 m and +1.2 m, while the average difference is -0.06 m with a standard deviation of 0.467 m. The density function reveals a better approximation of the theoretical gaussian distribution (dotted line).

### 5.2 Karlsruhe Results Comparing Co-located Elevation Rasters in Areas of Pre-selected Land Cover Type

An overview of all elevation difference statistics for the resampled 4.5 m rasters is presented in Tab. 1. In total, 5 urban test areas, 7 forest test areas, 2 water test areas, 8 vineyard test areas, 5 agricultural (bare soil) test areas, and 12 agricultural (vegetation cover) test areas were included in these calculations. The size of each test area is given. Elevation differences between the resampled rasters of the SAR and the laser ’ground’ data were calculated for each area: the number of differences calculated, the average difference and the standard deviation are shown. For the difference statistics betwen the SAR and the laser ’vegetation’ data set, only a few test areas qualified (land cover types ’urban’, ’forest’, and ’vineyard’). In addition, for urban test area 5 the differences have been calculated between the resampled rasters of the SAR and the complete laser (integrating ’ground’ and ’vegetation’) data set.

In detail, one can contrast the results for the ’original’ measurements in the agricultural test area 1 as shown in Fig. 2 with the results in Tab. 1. For the agricultural test area 1, the ’original’ measurements show an average difference of -0.06 m with a standard deviation of 0.467 m (calculated from 84 events), while - in the raster differences - the average amounts to +0.05 m with a standard deviation of 0.493 m (calculated from 2.796 events). For the majority of test areas, the results from both assessment methods were found to be consistent. For test area 1 of class ’urban’, a graphical representation of

| | area [m²] | difference Radar - Ground: number of points | difference Radar - Ground: average [m] | difference Radar - Ground: standard deviation [m] | difference Radar - Vegetation: number of points | difference Radar - Vegetation: average [m] | difference Radar - Vegetation: standard deviation [m] | difference Radar - Laser: number of points | difference Radar - Laser: average [m] | difference Radar - Laser: standard deviation [m] |
|---|---|---|---|---|---|---|---|---|---|---|
| **urban** | | | | | | | | | | |
| area 1 | 278.509 | 13.753 | 0,452 | 2,021 | 13.744 | -3,382 | 2,766 | | | |
| area 2.1 | 625.010 | 30.856 | 0,998 | 2,626 | 30.864 | -4,023 | 3,507 | | | |
| area 3 | 630.545 | 31.116 | 1,488 | 2,056 | 31.119 | -2,233 | 3,067 | | | |
| area 4 | 503.821 | 24.867 | 1,536 | 1,497 | 24.868 | -2,603 | 2,544 | | | |
| area 5 | 140.662 | 6.931 | 1,869 | 1,869 | 6.936 | -2,284 | 2,623 | 6.941 | -0,145 | 2,962 |
| total | 2.178.548 | 107.523 | | | 107.531 | | | 6.941 | | |
| **forest** | | | | | | | | | | |
| area 1.1 | 562.314 | 27.816 | 19,353 | 6,603 | 27.816 | 5,128 | 7,440 | | | |
| area 2.1 | 492.714 | 24.338 | 18,279 | 7,249 | 24.343 | 7,416 | 8,018 | | | |
| area 2.2 | 529.811 | 26.160 | 20,537 | 4,833 | 26.160 | 5,514 | 7,729 | | | |
| area 3.1 | 618.004 | 30.505 | 21,587 | 6,581 | 30.511 | 5,096 | 7,577 | | | |
| area 4.1 | 424.913 | 20.980 | 18,771 | 6,792 | 20.980 | 6,866 | 8,630 | | | |
| area 4.2 | 504.388 | 24.911 | 21,190 | 5,520 | 24.912 | 6,162 | 8,173 | | | |
| area 5.1 | 503.170 | 24.857 | 18,231 | 5,270 | 24.857 | 3,375 | 6,080 | | | |
| total | 3.635.314 | 179.567 | | | 179.579 | | | | | |
| **water** | | | | | | | | | | |
| area 2 | 15.677 | 762 | 4,073 | 3,864 | | | | | | |
| area 5 | 2.437 | 116 | 0,178 | 0,714 | | | | | | |
| total | 18.114 | 878 | | | | | | | | |
| **vineyard** | | | | | | | | | | |
| area 1 | 221.446 | 10.933 | -0,166 | 0,455 | | | | | | |
| area 2 | 52.167 | 2.595 | -0,034 | 0,738 | | | | | | |
| area 3 | 286.460 | 14.137 | 0,034 | 0,595 | 14.128 | -1,206 | 1,290 | | | |
| area 4 | 121.903 | 6.019 | 0,758 | 0,482 | 6.016 | -0,733 | 1,656 | | | |
| area 5 | 63.910 | 3.148 | 1,252 | 0,654 | 3.148 | 0,428 | 1,867 | | | |
| area 6 | 170.002 | 8.396 | 0,271 | 1,119 | 8.396 | -0,591 | 1,654 | | | |
| area 7 | 69.905 | 3.441 | 0,330 | 0,623 | 3.440 | -0,503 | 1,325 | | | |
| area 8 | 45.935 | 2.264 | 0,036 | 0,482 | 2.262 | -0,932 | 1,340 | | | |
| total | 1.031.727 | 50.933 | | | 37.390 | | | | | |
| **agricultural areas (bare soil)** | | | | | | | | | | |
| area 1 | 56.804 | 2.796 | 0,054 | 0,493 | | | | | | |
| area 5 | 30.480 | 1.511 | -1,507 | 0,584 | | | | | | |
| area 6 | 29.575 | 1.453 | -0,217 | 0,313 | | | | | | |
| area 7 | 39.121 | 1.925 | -0,417 | 0,650 | | | | | | |
| area 8 | 22.479 | 1.109 | 0,089 | 0,207 | | | | | | |
| total | 178.458 | 8.794 | | | | | | | | |
| **agricultural areas (vegetation covered)** | | | | | | | | | | |
| area 1 | 89.118 | 4.399 | -1,748 | 0,373 | | | | | | |
| area 4 | 69.301 | 3.422 | -1,300 | 0,313 | | | | | | |
| area 5 | 125.585 | 6.195 | -1,591 | 0,522 | | | | | | |
| area 6 | 446.115 | 22.028 | -2,468 | 0,439 | | | | | | |
| area 7 | 66.546 | 3.260 | 0,334 | 0,229 | | | | | | |
| area 8 | 25.360 | 1.246 | 0,204 | 0,378 | | | | | | |
| area 10 | 31.016 | 1.531 | -0,024 | 0,426 | | | | | | |
| area 11 | 24.469 | 1.209 | 0,303 | 0,325 | | | | | | |
| area 12 | 22.688 | 1.114 | -0,220 | 0,280 | | | | | | |
| area 13 | 20.329 | 998 | 0,170 | 0,218 | | | | | | |
| area 14 | 44.890 | 2.211 | -0,353 | 0,414 | | | | | | |
| area 15 | 59.895 | 2.952 | -0,100 | 0,358 | | | | | | |
| total | 1.025.310 | 50.565 | | | | | | | | |

Table 1: Resampled rasters: overview of the statistical figures of all test areas

the statistical evaluation of elevation differences between the resampled SAR and laser 'ground' raster data sets is shown in Fig. 3. 13.753 differences were included, ranging from -5.0 m up to +11.98 m. The average elevation difference amongst these samples was +0.45 m with a standard deviation of 2.02 m. In Tab. 1, it is shown that - for the same test area - the differences between the SAR and the laser 'vegetation' data sets amount to an average of -3,38 m with a standard deviation of 2,76 m. Evidently, the elevation measurements of the interferometric SAR are significantly lower than those of the laser scanner. This can be attributed to the upper edge of the vegetation cover which may also include roof tops.

### 5.3 Intermap Results Comparing Co-located Elevation Rasters (Post-selected Bald-Earth)

The radar and laser DEMs are presented as colorized, shaded-relief views in Fig. 4b and 4c, respectively, along with a common color scale bar. Due to the limited number of pages and space for this report, the quality of the figures appears to be degraded when compared to image resolution and colour depth available. Areas that are colorized as white are due

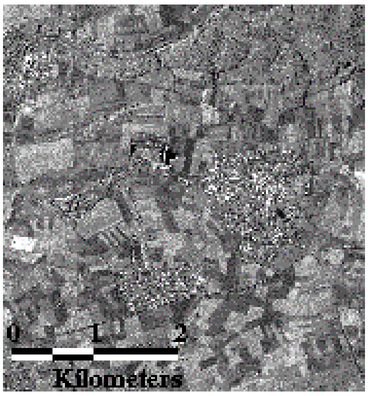


Figure 4a: STAR-3i Magnitude Image

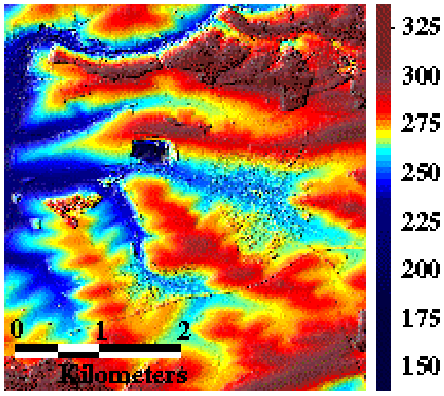


Figure 4b: STAR-3i DSM; Elevation shown in meters

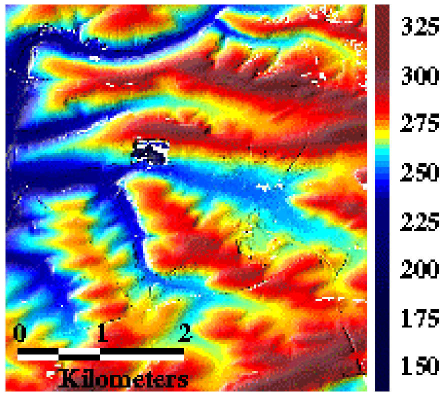


Figure 4c: Laser DTM; Elevation shown in meters

to the absence of data within the 15 m search radius. Inspection of these overview figures reveals immediately that while the general detail is very similar, the radar data (DSM) has retained effects of forests, buildings, objects on the surface. The laser DTM has successfully removed most of these, although some residual elevation effects remain, particularly in the urban areas. The difference surface (radar DSM minus laser DTM) is shown in Fig. 4d along with its color scale bar.

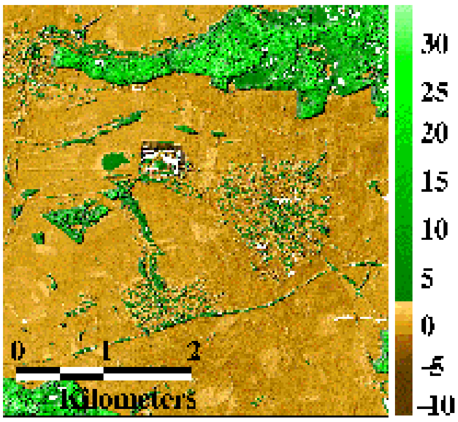


Figure 4d: Difference Surface (Radar minus Laser); Difference shown in meters

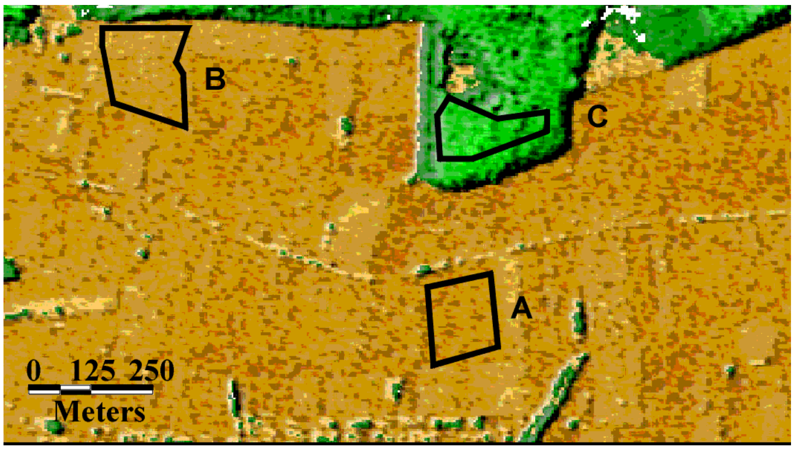


Figure 5: Zoomed Difference Surface

The color scale bar has been selected to show all positive height differences greater than approx. 2 m as green, while the micro-differences are colorized as shades of brown and cream. These micro-differences are due to a superposition of three effects: (1) systematic errors, (2) random noise errors, and (3) real terrain coverage differences (e.g., agricultural crops). To illustrate the magnitude of these three effects, statistics have been acquired for sub-areas denoted as A, B and C in Fig. 5, representing land-cover types 'bald-earth', 'agricultural crops', and 'forest', respectively. The results are shown in Tab. 2. The mean offset for the bald-earth case is about 50 cm and is due to a combination of systematic errors from both radar and laser, and perhaps transformation errors. The 28 cm standard deviation of the bald-earth example is essentially the noise floor of the radar (assuming the noise floor of the laser to be significantly smaller). The mean difference in the crop sub-area is 0.66 m, but when the common systematic error is removed, the effective height of the crop is 1.13 m. The noise is similar to the bald-earth case. The effective height of the forest sample, on the other hand, is about 21 m,

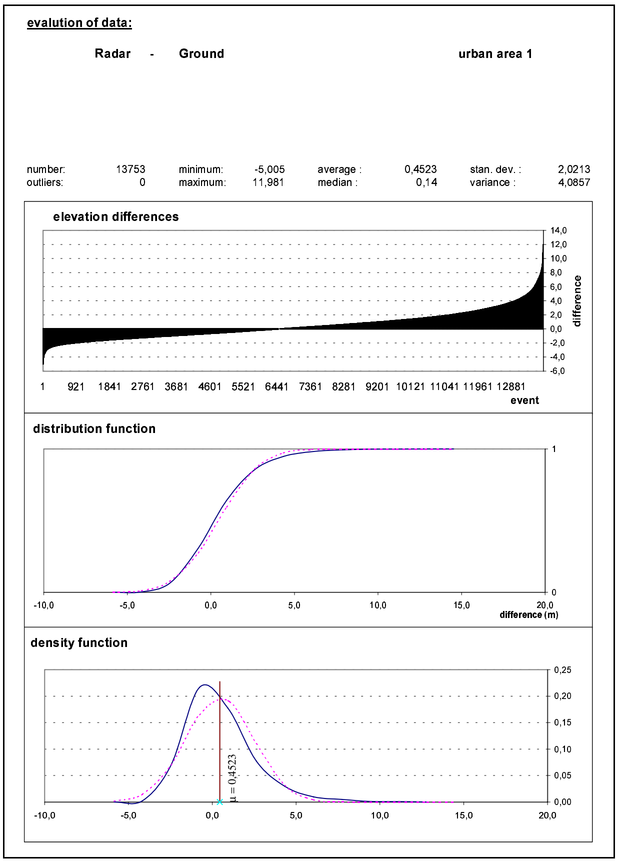


Figure 3: Resampled rasters: statistics of test area 1 (class 'urban')

| area | land cover | mean (m) | std. dev. (m) |
|---|---|---|---|
| A | bald earth | -0.47 | 0.28 |
| B | crops | 0.66 | 0.34 |
| C | forest | 21.04 | 2.16 |
| overall | bald earth | -0.50 | 0.48 |

Table 2: Difference Surface Statistics

with a standard deviation of 2.16 m, which reflects the variability of the canopy even in a relatively homogeneous sub-area. Similar to this procedure, elevation difference statistics were calculated for 67 sub-areas throughout the entire test area. The results of the aggregated statistical analysis are also shown in Tab. 2, labelled as 'overall'. In this instance, the standard deviation is 48 cm compared to the typical noise floor of about 30 cm. This is because, over the large test area, spatially variable systematic errors contribute to the increased standard deviation.

## 6 COST ESTIMATION FOR THE DEM GENERATION

It is instructive to compare prices of products derived from the two technologies. From previous experience, the cost (in Germany) of acquiring a data set of coordinated elevation measurements through a single flight airborne mission of a laser scanner system amounts to approx. US$ 200.- per $km^2$. The cost figure rises significantly for small areas, i.e., less than 100 $km^2$. This does not include resampling to a raster DTM and final editing. In this case, the cost for large area data production may double to approx. US$ 400.- per $km^2$. Complex, multi-path flights may increase the cost by additional factors. The STAR-3i system described here is optimized for large area data acquisition. Prices for DEM data that is licensed DEM data (i.e. non-proprietary to the customer) are published (www.globalterrain.com) and depending on the type of product, location and volume discounts, are in the range of US$ 15 to 40 per $km^2$. Proprietary data prices are typically higher (about factor 2) than the licensed prices, but still considerably less than the standard laser scanner prices that have been observed to date.

## 7 CONCLUSIONS

All accuracy evaluations confirmed that the elevation differences between the data sets derived from the interferometric SAR and the laser scanner are very small for bare soil areas: the mean difference is close to 0, while the standard deviation ranges from 20 cm to 60 cm which mostly reflects the inevitable noise level. For agricultural test areas covered by crops, the differences varied to a greater extend, but were still in the one sigma range of 50 cm to 100 cm. In contrast, the differences for forested and urban areas were significantly greater, which reflect the fact that the radar produced a DSM, measuring within the canopy or on top of the buildings, whereas the laser was reporting bald-earth, edited elevations. For applications requiring bald-earth elevations, it would be necessary to remove the trees and buildings from this DSM. The cost differential between the radar and laser-derived products makes the latter an attractive alternative for large area DTM acquisitions with the above-noted qualifications in forested and urban areas.

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