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Change Detection in High-Resolution Land Use/Land Cover Geodatabases (at Object Level)

Emilio Domenech, Clément Mallet

A survey on state of the art of 3D Geographical Information Systems

Volker Walter

Dense Image Matching Final Report

Norbert Haala

Crowdsourcing in National Mapping

Peter Mooney, Jeremy Morley

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„Change Detection in High-Resolution Land Use/Land Cover

Geodatabases (at Object Level)“ ..... 9

1.	Introduction.....	11
2.	Objectives.....	12
3.	Study areas and data pre-processing .....	12
3.1.	Alcalá de Henares data.....	14
3.2.	Valencia data .....	14
3.3.	Murcia data.....	16
4.	Methodology .....	16
4.1.	Classification in basic land cover.....	17
4.1.1.	Image segmentation.....	18
4.1.2.	Region adjacency graph .....	20
4.1.3.	Image classification improvement using Dempster-Shafer theory.....	21
4.1.4.	Shadow removal .....	24
4.1.4.1.	Computing the shadow layer.....	24
4.1.4.2.	Assigning classes to shadow regions.....	25
4.2.	Multi-source attribute extraction and land use classification.....	27
4.2.1.	Feature extraction.....	28
4.2.1.1.	LiDAR-based features .....	30
4.2.1.2.	Spatial context features .....	31
4.2.2.	Object classification .....	31
4.2.2.1.	Object and class definition .....	31
4.2.2.2.	Selection of descriptive features.....	33
4.2.2.3.	Classification procedure .....	35
4.3.	Change detection.....	36
4.3.1.	Change detection evaluation .....	36
5.	Results.....	38
5.1.	Phase I results: generation of basic land cover classes .....	38
5.2.	Phase II results: multisource attribute extraction and land use classification ....	41
5.3.	Change detection results .....	45
5.3.1.	Change detection in periurban areas .....	45
5.3.2.	Change detection in rural areas .....	46
5.4.	Application to quantify polygon attributes in SIOSE database .....	48
6.	Conclusions.....	54
7.	Future Studies .....	54
8.	References.....	57

*(b) Volker Walter:*  
 „A survey on state of the art of 3D Geographical Information Systems“ ..... 65

1	Introduction.....	66
2	Participants.....	66
3	Evaluation of Questionnaire Part A.....	68
4	Questionnaire Part B.....	82
5	Summary.....	86
6	Conclusions and Outlook.....	86
	Annex A: Participating Institutions.....	88

*(c) Norbert Haala:*  
 „Dense Image Matching Final Report“ ..... 115

1	Introduction.....	116
2	The EuroSDR Project on Dense Image Matching – Data sets and deliverables.....	117
3	Test participants, investigated software systems and used hardware environment .....	120
4	Evaluation of DSM Quality .....	122
	4.1. Test area Vaihingen/Enz.....	123
	4.2. Test area München .....	133
5	Conclusions.....	142
6	References.....	143

<i>(d) Peter Mooney, Jeremy Morley:</i> „Crowdsourcing in National Mapping“ .....	147
Abstract .....	148
Acknowledgement .....	149
Preface	148
1 Introduction and Motivation .....	150
2 Project Development Timeline.....	151
3 Projects selected for funding.....	153
4 Details of Individual Project Reports.....	154
4a: Project 1: Collection and visualization of alternative tourism sites and objects in Lithuania .....	155
4.b Project 2: Incidental Crowdsourcing.....	157
4.3: Project 3: Ontology based Authoritative and Volunteered Geographic Information (VGI) integration.....	158
4.4 Project 4: Conflation of Crowdsourced Data .....	160
4.5 Project 5: Characterising the use of vernacular placenames from crowd sourced data and a comparison with NMA Data.....	162
5 Conclusions and Recommendations. ....	164
References.....	166

**EuroSDR-Project**  
**Commission 2**  
**“Benchmark on Image Matching”**  
**Final Report**

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## Abstract

Both improvements in camera technology and the rise of new matching approaches triggered the development and upgrade of suitable tools for image based 3D reconstruction by research groups and vendors of photogrammetric software. Meanwhile, dense pixel-wise matching enables the photogrammetric generation of dense 3D point clouds and Digital Surface Models from highly overlapping aerial images. In order to evaluate the quality of these matching algorithms in terms of accuracy and reliability, the European Spatial Data Research Organisation (EuroSDR) initiated a benchmark on image based DSM generation in February 2013. The test is based on two representative image blocks to be processed by different groups with their respective software systems. By compiling these results, this report aims to provide a profound insight to the landscape of dense matching algorithms while evaluating the current potential of image based photogrammetric data collection.

## Preface

A first EuroSDR project on *Benchmarking of Image Matching Approaches for DSM Computation* was already launched in 2010 by Marc Pierrot Deseilligny and Grégoire Maillet (IGN). This project ended after the EuroSDR Commission II workshop on *High Density Image Matching for DSM Computation*, in February 2012 (EuroSDR 2012). Also motivated by the success of this workshop, EuroSDR started the follow up project *Benchmark on Image Matching* in October 2012. This project was led by the principals Prof. Dr. Norbert Haala, Institute for Photogrammetry, Stuttgart University, Wolfgang Stoessel, Landesamt für Vermessung und Geoinformation Bayern (LVG) and Dr. Michael Gruber, Microsoft Photogrammetry. This one year project phase is now concluded by the submission of this final report.

## 1 Introduction

Recent innovations in matching algorithms considerably improved the quality of elevation data derived from aerial images. Traditional stereo-matching, originally introduced more than two decades ago, typically applies feature based algorithms. These algorithms first extract feature points and then search the corresponding features in the overlapping images (Heipke 1993). The restriction to matches of selected points helps to provide correspondences at high certainty. Additionally, it avoids problems due to limited computational resources, which originally was another motivation to use such feature based matching approaches. In contrast, recent stereo algorithms aim on dense, pixel-wise matches. By these means 3D point clouds and Digital Surface Models (DSM) are generated at a resolution, which corresponds to the ground sampling distance GSD of the original images. To enable pixel matches even for regions with very limited texture, additional constraints are required. Local or window based algorithms like correlation use an implicit assumption of surface smoothness since they compute a constant parallax for a window with a certain number of pixels. In contrast, so-called global algorithms use an explicit formulation of this smoothness assumption, (Szeliski, 2010). The resulting global optimization problem can for example be solved very efficiently by recursive algorithms like scanline optimization. A very popular and well performing approach in this context is semi-global matching (Hirschmüller, 2008). It evaluates a cumulative cost function from multiple scanline directions. The approach produces accurate results very efficiently, especially when combined with sophisticated aggregation strategies (Szeliski, 2010). Thus, this technique is currently

implemented by a number of research institutes and photogrammetric software vendors within their software tools for image based 3D point cloud generation. These developments are considerably changing the landscape of photogrammetric data processing.

Especially during such stages of rapid progress, benchmarks which measure the performance of state-of-the-art algorithms have proven to be extremely useful for supporting the further development. Well known examples in the context of matching algorithms are the Middlebury Stereo Vision Page (Scharstein, & Szeliski 2002) or the benchmark on multi-view stereo reconstruction (Seitz et.al. 2006). These benchmarks provide general purpose datasets through a platform, which additionally allows for an upload of the results by the respective participant. These are then compared to available reference data to compute suitable quality metrics. While these projects emerged from the Computer Vision community, a test on the performance of photogrammetric digital airborne camera systems was organized under the umbrella of the German society of Photogrammetry, Remote Sensing and Geoinformation (DGPF) by Cramer (2010). There the potential of photogrammetric 3D data capture from automatic image matching was already demonstrated by Haala et.al. (2010). Also in view of the rapid progress in software technology, EuroSDR started another initiative to evaluate the ongoing developments in image based DSM generation in October 2012. The benchmark was announced via the EuroSDR web-page (EuroSDR, 2013a), which was also used to disseminate the test data sets to potential participants. Based on the given images and camera parameters, test participants then had the opportunity to produce Digital Surface Models with their software system. After the results were sent back, the project team started further evaluation. These results were presented and discussed during the 2<sup>nd</sup> EuroSDR workshop on *High Density Image Matching for DSM Computation* held from 13th to 14th June 2013 at the Federal Office for Metrology and Surveying in Vienna (EuroSDR 2013b). There the respective groups could demonstrate their state-of-the-art in high quality image based DSM generation and discuss future applications and additional needs together with potential users. Since the workshop brought together software developers, distributors and users of dense matching software it was a very suitable platform for a first review on the outcomes of the benchmark.

The following section of this report first presents the test data sets, which consists of image blocks for two representative areas. Section 3 then introduces the different software systems used during the test while section 4 compares, evaluates and discusses the respective results from these software systems as generated by the test participants.

## **2 The EuroSDR Project on Dense Image Matching – Data sets and deliverables**

In order to limit the effort required for data processing by potential benchmark participants, the test was restricted to two subsets of aerial image flights. To achieve representative data sets, two aerial image sub-blocks of different landuse and block geometry were selected.

The first data set, Vaihingen/Enz is an example for data typically collected during state-wide DSM generation at areas with varying landuse. As it is visible from the ortho image and the DSM of the test area in Figure 1 it covers a semi-rural area at undulating terrain. Elevation differences of 200m occur between the river valley and the upper area. The data are a subset from a flight collected during the project on Digital Airborne Camera Evaluation of the German Society of Photogrammetry, Remote Sensing and Geoinformation (DGPF) (Cramer, 2010).



Figure 1: Vaihingen/Enz test area with ortho image and DSM.

Both ground sampling distance (GSD) and overlap of the image block are rather moderate. This situation is typical for most flights captured for national mapping agencies. The aerial images were captured by an UltraCam-X at height above ground of 2900m and a GSD of 20cm. For image matching the PAN images had to be used, which were made available as Tiled Tiff uncompressed 8 bit/pix with 9420x14430pix at 136Mpix/image.

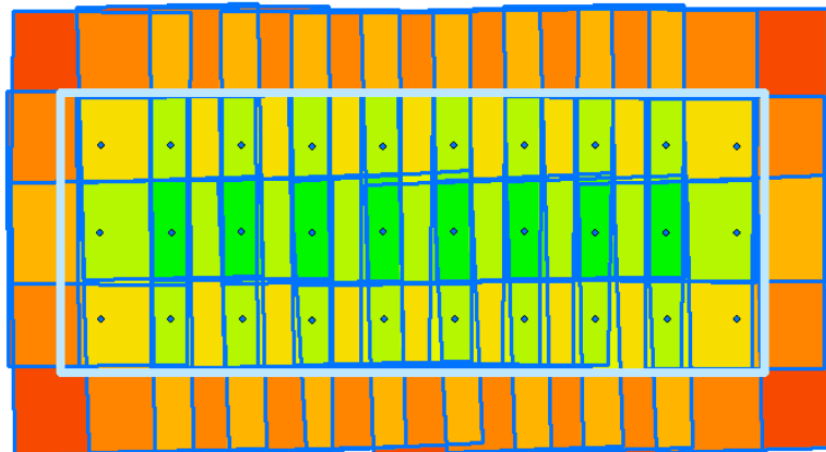


Figure 2: Vaihingen/Enz: Image overlap (maximum nine-folded) with image footprints and camera stations. The area to be processed is depicted as light blue rectangle

The sub-block selected for the benchmark is depicted in Figure 2. It consists of 3 strips with 10 images each. Figure 2 additionally visualizes the corresponding 30 camera stations, which are represented by the blue points. The respective image footprints are depicted by rectangles in the same color. One of the main factors which influence the quality of image based surface reconstruction is the amount of image overlap. In Figure 2 the number of images available for each terrain point is represented by the color coded map. For the Vaihingen/Enz sub-block, the available overlap of 63% in flight and 62% cross flight results in variations from one-folded areas (red) to nine-folded overlap (green). In Figure 2 these areas are represented in red and dark green, respectively. As it is also visible, usually four to nine images were available for the central part of the block, where the DSM had to be generated. During the test a DSM had to be generated for the central part of the block at a size of 7.5kmx3.0km. This part is highlighted by the rectangle with light blue outlines and corresponds to the ortho image and DSM already shown in Figure 1. Participants of the benchmark were asked to generate a DSM raster at a grid with of 0.2m, which resulted in a DSM raster of 37500x15000 pixels.

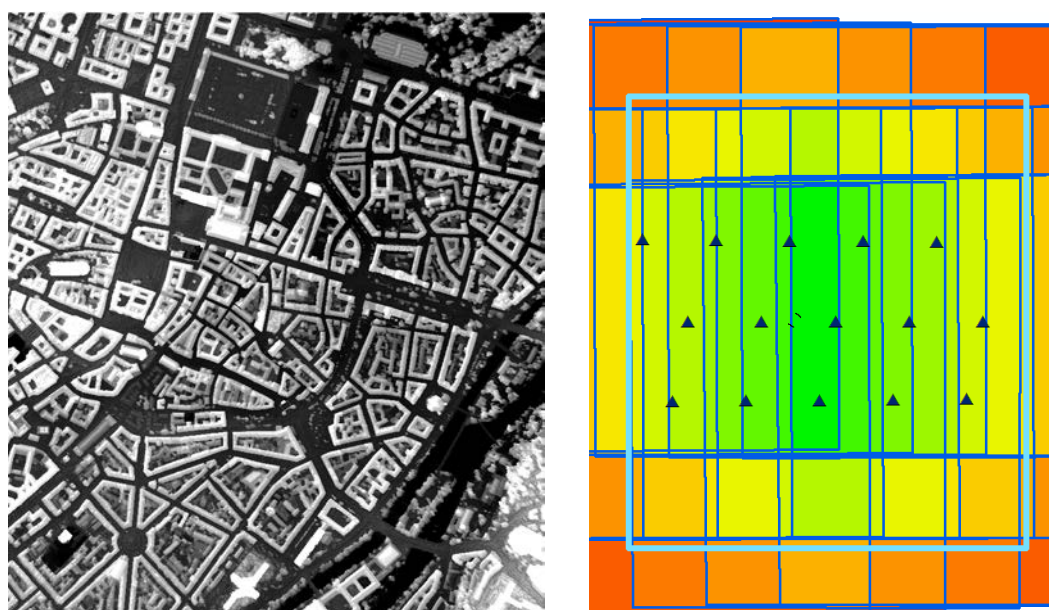


Figure 3: München test area with DSM (left) and color-coded image overlap (maximum 15 folded) with image footprints, camera stations and area to be processed (right).

The second test area München is representative data collection in densely built-up urban areas. For such applications, images are usually captured at a higher overlap and resolution. As it is visible from the grey coded DSM representation in Figure 3 (left), this urban data set covers the central part of the city at a size of 1.5kmx1.7km. The imagery was captured by a DMC II 230 camera at a GSD of 10cm. Each image has a size of 220 Mpixel/image (15552x14144 pix) at 16 bit/pix. The image sub-block to be processed consists of 3 image strips with 5 images each. In the right part of Figure 3, the camera stations are represented by dark blue triangles with the corresponding image footprints depicted as rectangles in the same color. The area to be processed is highlighted by the light blue rectangle. The image block was captured with 80% in flight and 80% cross flight overlap, which results in up to fifteen-folded object points in the central part of the test area. In Figure 3 (right) this maximum overlap is depicted in dark green. This large overlap provides a considerable redundancy during DSM generation. However, it reduces to five images per object pixel at the border of the area to be processed.





Figure 4: Visualisation of test area München

A textured DSM visualization for a part of the test area München is given in Figure 4. As it is visible, the area is rather flat but densely covered by buildings with heights of up to 50m. Thus, surface parts close to the building facades will frequently be subject to occlusions. This potentially aggravates the matching processes during DSM generation for such regions.

### 3 Test participants, investigated software systems and used hardware environment

To address a suitable number of participants, the test procedure for the benchmark was kept relatively simple. Since the main focus is on dense image matching, all participants had to use the orientation parameters made available for the image blocks without modification. Participants had to compute a DSM raster of predefined size and resolution as their final outcome.

These results were then sent to the project team for comparison and accuracy analysis. In addition to the required processing time, the participants were asked to provide further information on their available hardware environment and their processing strategy. These informations were retrieved by a questionnaire and also presented by the participants during the 2<sup>nd</sup> EuroSDR workshop on *High Density Image Matching for DSM Computation*. The following list briefly summarizes this information for each software system.

- **SocetSet 5.6 (NGATE)** from **BAE Systems** was presented by C. Ginzler from Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). He used an Intel Xeon CPU X5570 2.93 GHz and 24 GB memory. The required processing time for Vaihingen/Enz was 36h and 25h for München.
- B. Brunner from Forest Mapping and Management (FMM) Salzburg presented results from **Microsoft UltraMap V3.1**. This software can only be used from imagery captured by the UltraCam product family. Therefore, investigations were restricted to the Vaihingen/Enz data set. Furthermore, processing has to pass through all software modules. Since this includes Automatic Aerial Triangulation and color adjustment, the UltraMap results are based on an individual bundle block adjustment. Furthermore instead of the 8bit images

provided to the participants the originally 16bit imagery was used. The IT environment consisted of 32 Xeon E5-2630/i7 cores and 5 GPU's (1 Tesla K10, 4 Tesla M2090). For the 36 images of the Vaihingen/Enz block this comparable powerful environment resulted in a processing time of about 35min for data ingest and AAT while the DSM was computed in 27min.

- **Match-T DSM 5.5** from **Trimble/inpho** was presented by C. Ressler from the Department of Geodesy and Geoinformation (GEO) at TU Wien. He used an Intel Core i7 CPU, 3GHz with 4 cores and 8GB memory. Match-T itself matches only one image pair for each XY-location. To exploit the high image overlap all possible image pairs were matched during his investigations. The resulting DSMs were then fused using the in-house software systems Opals. Processing time for Vaihingen/Enz resulted in 23h for matching with Match-T and 38h for data import, gridding and fusion with Opals. For the München data set the numbers were 19h for matching with Match-T and 37h for processing with Opals.
- The **ImageStation ISAE-Ext** software was demonstrated by R. Schneider from **GEOSYSTEMS GmbH**, Germany. For the München test area processing was limited to 6 stereo models. The hardware environment of 2 Intel Xeon Quadcore Processors with 16GB RAM a computation time of 40min per stereo model and 4h for the complete block was achieved. For Vaihingen/Enz 33 stereo models were processed at an average computation time per stereo model of 20min. This resulted in 11h for stereo matching in total, followed by 21h for grid interpolation of the 580 million points to the required 20cm raster.
- P. Nonin from **Astrium GEO-Information Services** presented results for the **Pixel Factory** software. For his investigations a hardware configuration of 2 Xeon E5-2640, 2.5GHz with 2x6 cores was used. Results for the München area are based on the processing of 12 stereo pairs. Due to expected problems from moving shadows no cross-track matching was applied for this scene. Total time for DSM generation was 2h 12min. For Vaihingen/Enz 57 stereo pairs were processed in a total time of 3h 9min.
- M. Idrissa from the **Royal Military Academy (RMA)**, Brussels showed results for the **RMA DSM Tool**. For processing a Linux Cluster with more than 90 Fedora CPUs (Intel – 2.4 GHz) and more than 30 nodes with 272GB RAM (total) and a 1000Mbit/s network was used. Processing times for München was approximately 18min per stereo couple and about 5h for the complete block, for Vaihingen/Enz the numbers were 8min per stereo pair and again 5h in total.
- Results of the **Remote Sensing software package** from **Joanneum Research**, Graz, were presented by K. Gutjahr. He used a Windows PC Intel Xeon CPU E5-2650, 2.0 GHz with 16 Cores and 32GB RAM for processing. Processing time for Vaihingen/Enz for 57 stereo pairs summed up to 17h 17min for the processing steps preparation, normalization and prediction, matching, forward intersection, DSM generation and DSM finalization. Accordingly the processing time for München with 22 stereo pairs was 21h 39min.
- The software system **MicMac** developed at **IGN France** was presented by M. Pierrot-Deseilligny. Within MicMac multi image matching is realized by energy minimization either using graph cut or a modified dynamic programming/SGM approach. Vaihingen/Enz was processed within 6h and München in 12h.
- M. Rothermel presented results from the **SURE** software developed at the **Institute for Photogrammetry (IfP), University of Stuttgart**. It is based on a SGM variant with integrated coarse-to-fine strategy based on efficient implementation of SGM on dynamic data structures. He used a PC with one i7 CPU quadcore at 3.4GHz and 32GB Ram. For the

München data set in total 4h 13min were required. The processing time for Vaihingen/Enz summed up to 4h 37min. For an alternative implementation using an NVIDIA 580 GTX GPU and an i3 CPU, dual-core the Vaihingen/Enz data set was processed in 2h 50min.

- H. Hirschmüller, **German Aerospace Center (DLR)** provided results from a FPGA implementation of his SGM algorithm. Processing was realized on an Intel Xeon E5-1620 quad core PC. However, for processing a Virtex 6 FPGA board with 8GB Ram, connected to the PC via GigE was applied. With this configuration a processing time for the München data set of 5h 51min and 19h 31min for Vaihingen/Enz was recorded. These results were available before the workshop, however, no presentation was given
- Results from **Leica's XProSGM**, which is included within Intergraph ImageStation's ISAE-Ext for dense matching was provided after the workshop by Stephan Gehrke. Processing was realized for Munich on a i7-920 CPU quadcore at 2.67GHz, for the Vaihingen/Enz area on a i7-2600 at 3.4GHz. For Munich a total of 42 stereo pairs were processed to generate the DSM in 50.3 hours, for Vaihingen/Enz 87 image pairs were used in a processing time of in 26.8 hours.

In this research project commercial photogrammetric software systems were used by customers and vendors. Scientific staff from research institutes tested their self-developed systems. Typically, these software systems were developed for in house production and projects and then made available for the public under different license models. The above compilation also shows that very heterogeneous hardware environments were used during processing. It spread from standard desktop PCs with single to multi core to the use of low-end to multiple high-end graphics cards to the application of computer clusters. Due to the considerable amount of data to be processed, time required for DSM computation is additionally influenced by reading and writing operations. Thus, efficiency of data ingest also depends on the available storage system and network environment. Finally, processing time is influenced by adjusting the respective strategy, which e.g. defines the required amount of stereo-pairs to be processed. As an example, some of the participants have used cross-track matching i.e. images from different strips to form stereo pairs, while others have only used stereo pairs from the same strip for the matching. This is the reason why the reported processing times should not be regarded as a fixed number but as a hint to the capacity of the area covering data collection of the respective software systems. Further information is also available from the presentations in the workshop proceedings (Fritsch et. al., 2013).

#### 4 Evaluation of DSM Quality

In order to assess the quality of DSM data sets, a comparison to a reference surface is most suitable. In principle airborne LiDAR can provide the required independent measurements. However, differences of DSM from image matching to such a reference surface cannot exclusively be put to errors of the matching process. Deviations can for example occur due to a time gap between image and LiDAR data acquisition. For the Vaihingen/Enz test area LiDAR and imagery were captured with a lag of 4 weeks. This resulted in considerable elevation differences due to plant growth and harvesting (Haala et.al. 2010). Height variations can additionally result from the different measurement principles. Light pulses from airborne laser scanning partially penetrate a tree canopy, while matching will most probably relate to the visible surface. Finally, pixel-wise matching reconstructs surface representations at a resolution, which is frequently not available from standard LiDAR flights. For Vaihingen/Enz the benchmark aimed at a 20cm grid width of the DSM. This

corresponds to 25pts/m<sup>2</sup>, while LiDAR data was only available with a point density of 6.7 pts/m<sup>2</sup>. Similarly, the 10cm grid to be generated for München equals to 100pts/m<sup>2</sup>, while the available LiDAR points have a density of 4 pts/m<sup>2</sup>. Due to these difficulties in providing suitable ground truth from independent LiDAR measurements, an alternative approach was followed. The reference surface used for our investigations is based on a median DSM, which was computed from the results of all participants. While this median DSM does not provide independent ground truth at a higher order accuracy it still can be used very well to illustrate differences between the respective solutions.

#### 4.1. Test area Vaihingen/Enz

Test results for the Vaihingen/Enz area are depicted in Figure 5 to Figure 18. For better visibility only a smaller part of the test area is shown. Figure 5 presents an ortho image of this part, a shaded representation of the median DSM used as a reference surface is given in Figure 6. The RMS differences of all solutions to this DSM are shown in Figure 7. For better visualization, this color coded representation is overlaid to a shaded relief of the median DSM. Obviously elevation differences to the median surface increase at the shaded area of the quarry. Larger differences are also experienced in the river area, as well as in the vicinity of patches of trees and in the area of the vineyards. The individual differences of all available solutions to the median DSM are then shown from Figure 8 to Figure 18. Despite the fact that larger differences occur, color coding was always limited to differences between -2m and +2m.

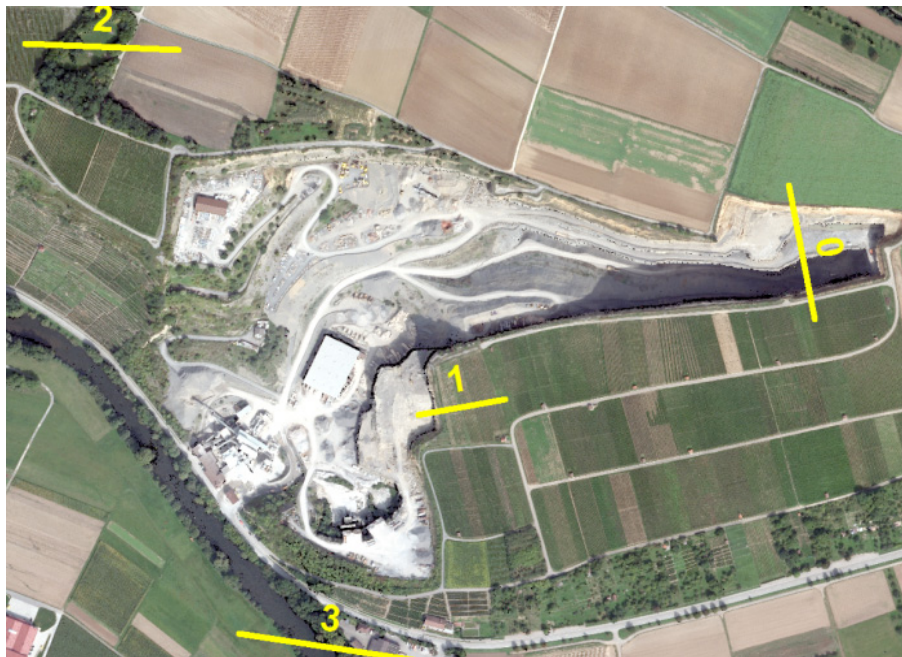


Figure 5: Ortho image of Vaihingen/Enz subsection with profile lines





Figure 6: Median DSM for all solutions of the Vaihingen/Enz subsection.



Figure 7: RMS differences for all solutions for a Vaihingen/Enz subsection.






Figure 8: Match-T, DSM differences  $<-2m$    $>2m$




Figure 9: Joanneum DSM differences,  $<-2m$    $>2m$






Figure 10: IfP Sure DSM differences, <-2m  >2m




Figure 11: IGN MicMac DSM differences, <-2m  >2m






Figure 12: GeoSystems DSM differences,  $<-2\text{m}$    $>2\text{m}$




Figure 13: UltraMap DSM differences,  $<-2\text{m}$    $>2\text{m}$






Figure 14: DLR-SGM DSM differences  $<-2m$    $>2m$



Figure 15: Astrium Pixel-Factory, DSM differences  $<-2m$    $>2m$






Figure 16: RMA, DSM differences  $<-2m$    $>2m$





Figure 17: SocetSet, DSM differences  $<-2m$    $>2m$



Figure 18: XProSGM, DSM differences <-2m  >2m

The DSM differences in Figure 8 to Figure 18 show, that apparently all elevations are very similar for the well illuminated area of the quarry, while large differences occur for some solutions at the area subject to cast shadow. Deviations also seem to increase at the repetitive patterns of the vineyards. For a quantitative analysis of DSM differences in these areas, elevation profiles from the available DSM solutions were additionally investigated. Figure 5 shows these lines overlaid to the ortho image.

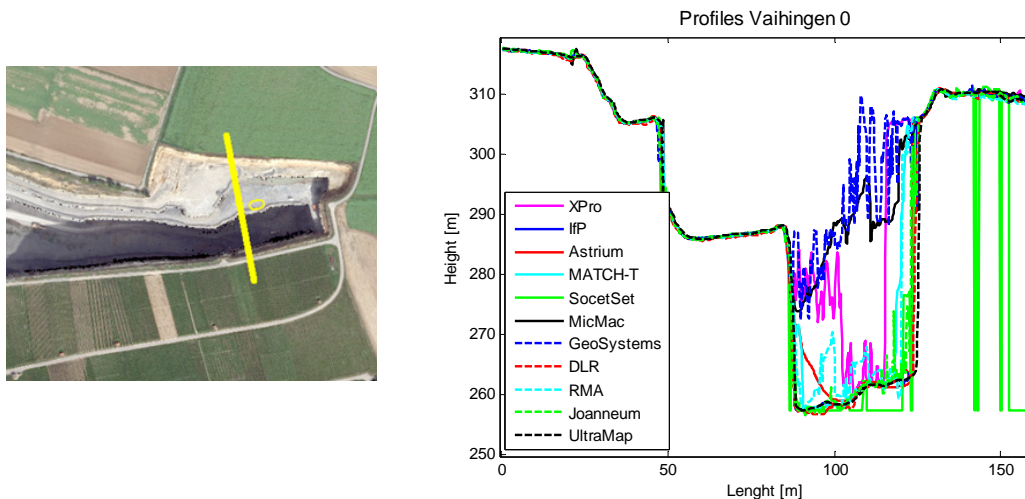


Figure 19: DSM-profile 0: Quarry 1

The different profiles are visualized in Figure 19 to Figure 22 with the corresponding section of the ortho image on the left. Figure 19 shows profile line 0 at the quarry area, which is partly subject to a cast shadow. Within this shadow area profiles from GeoSystems (dashed blue line) MicMac (solid black) and XPro (solid magenta) appear higher than the median DSM. Furthermore, the profile from the SocetSet DSM (solid green) contains a considerable



amount of no-data areas. The RMA profile (dashed light blue) is relatively noisy, while for Astrium (solid red) a certain smoothing can be observed.

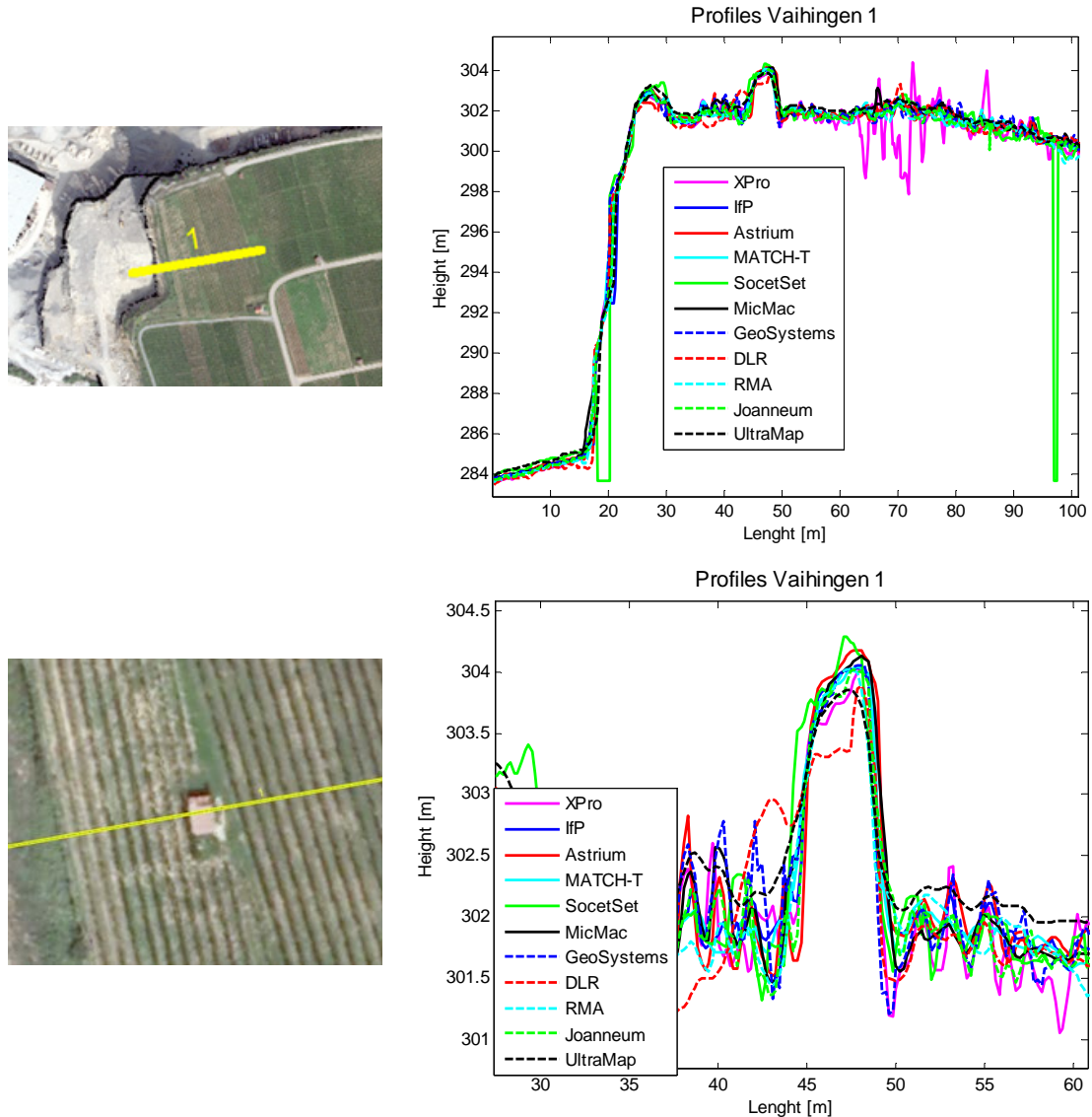


Figure 20: DSM-profile 1: Quarry 2 and vineyard

Figure 20 shows profile 1, located at another slope of the quarry. In contrast to profile 0 the complete area is well illuminated. Apparently, this is beneficial for the DSM generation. Except for a no-data area from SocetSet, all solutions are relatively consistent. The profiles additionally cover a vineyard. This part is depicted in a more detailed view in the bottom of Figure 20. Apparently this type of landuse increases the differences between the respective solutions. This is possibly due to the fact that the depicted rows of vines have a size close to the 20cm GSD of the available imagery. Still, some solutions like Astrium (solid red), MicMac (solid black), and IfP-SURE (solid blue) at least partially resolve these structures. Furthermore, almost all solutions are able to reconstruct the shape of the small hut in the center of the scene. At such an object surface which is not subject to problems for image matching, differences between almost all solutions are in the pixel level of 20cm.

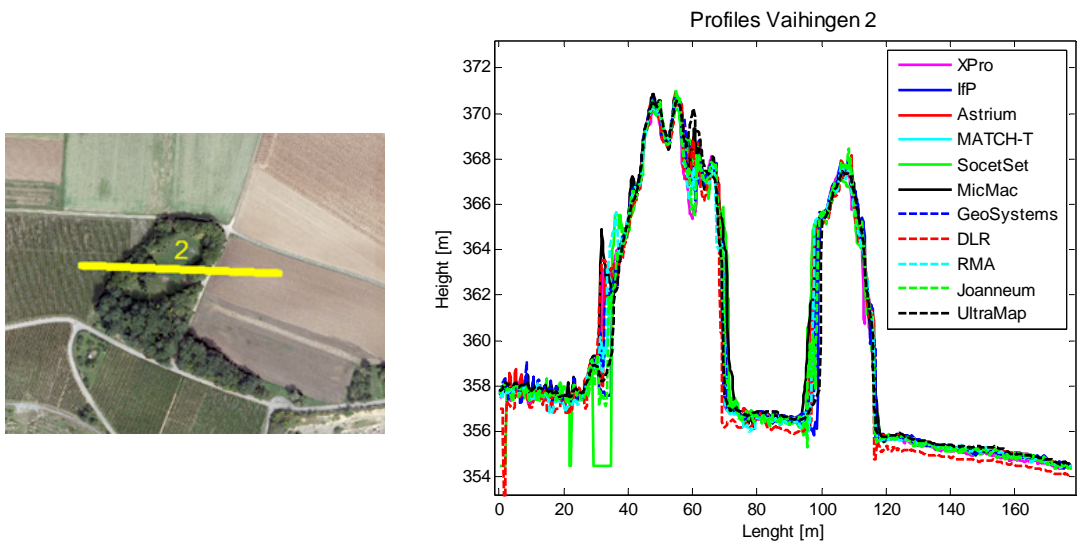


Figure 21: DSM-profile 2: Trees

Profile 2 in Figure 21 is situated at an area with patches of trees. Differences between the respective solutions mainly occur at the tree borders, for the bald earth on the right part of the profile results are remarkably consistent. Still, the profile from DLR (dashed red) has a constant offset compared to all other solutions. This is also visible in the difference image of Figure 14. The offset did not occur for a DSM additionally provided by DLR from a CPU based solution. However, the supposed problem in the investigated FPGA solution could not be fixed before finalizing the benchmark.

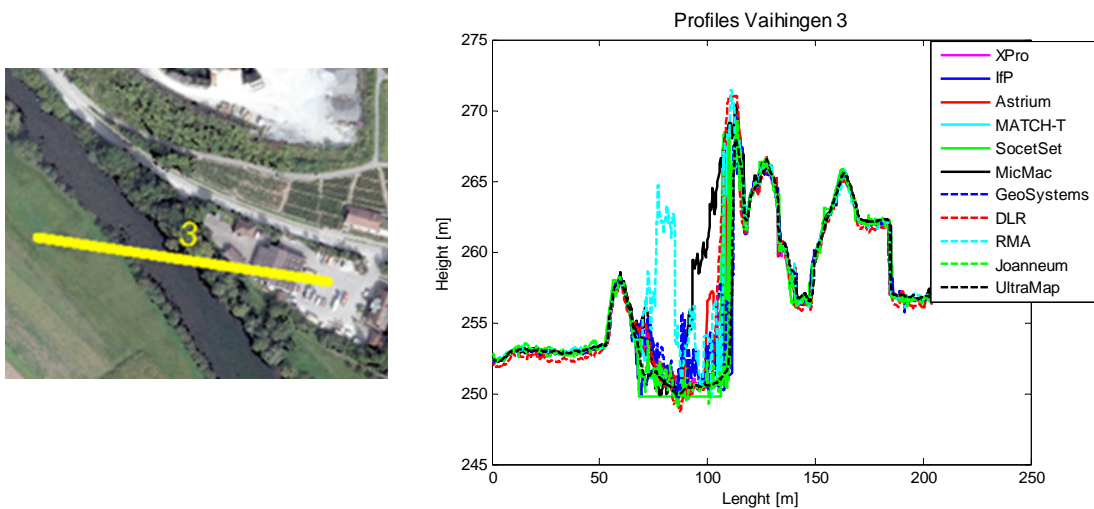


Figure 22: DSM-profile 3: Building and water

The final profile investigated for the test area Vaihingen/Enz is shown in Figure 22. The first part covers some buildings on the right and then crosses the river. Since water surfaces are almost impossible to reconstruct from image matching, larger differences of the DSMs occur. However, the solution from UltraMap (dashed black) is remarkably smooth. This is already obvious from the RMS differences of all solutions in Figure 7.

#### 4.2. Test area München

Figure 23 to Figure 38 show results for the urban test area München. Again, only a subsection is depicted for better visibility. Figure 23 shows the ortho image of the subsection, the median DSM is depicted in Figure 24. As already discussed, the UltraMap software is not able to process imagery from the DMC II camera, which was used to capture the München area. Due to this reason, results were only available from the remaining 10 software solutions. The individual DSM differences to the median DSM again color coded between -2m and +2m are shown in Figure 26 to Figure 35. Figure 25 shows the RMS differences of all DSM to the median. Since the result from SocetSet depicted in Figure 34 considerably deviated from all other results, this data set was not used during computation of these RMS values.

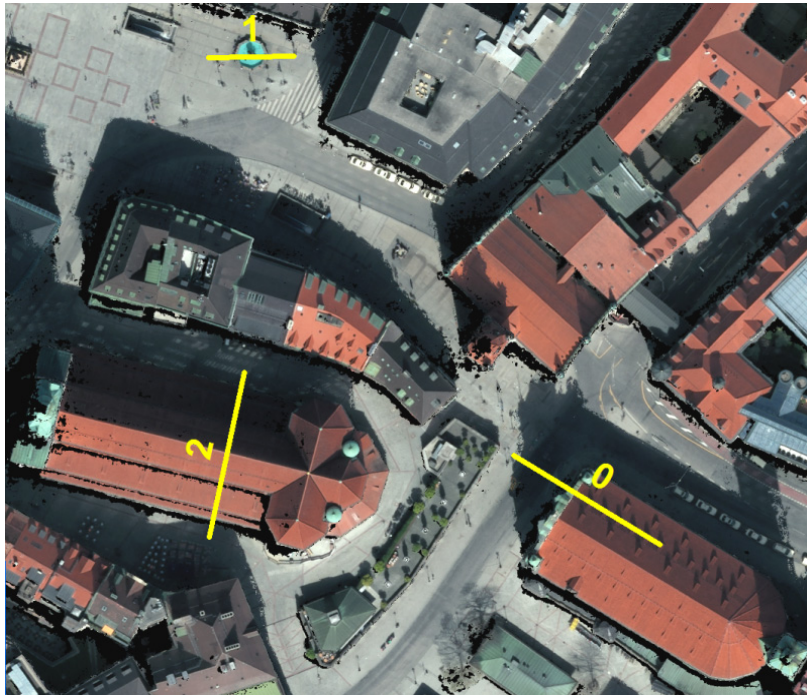


Figure 23: Ortho image of München subsection with profile lines





Figure 24: Median DSM for all solutions of the München subsection.

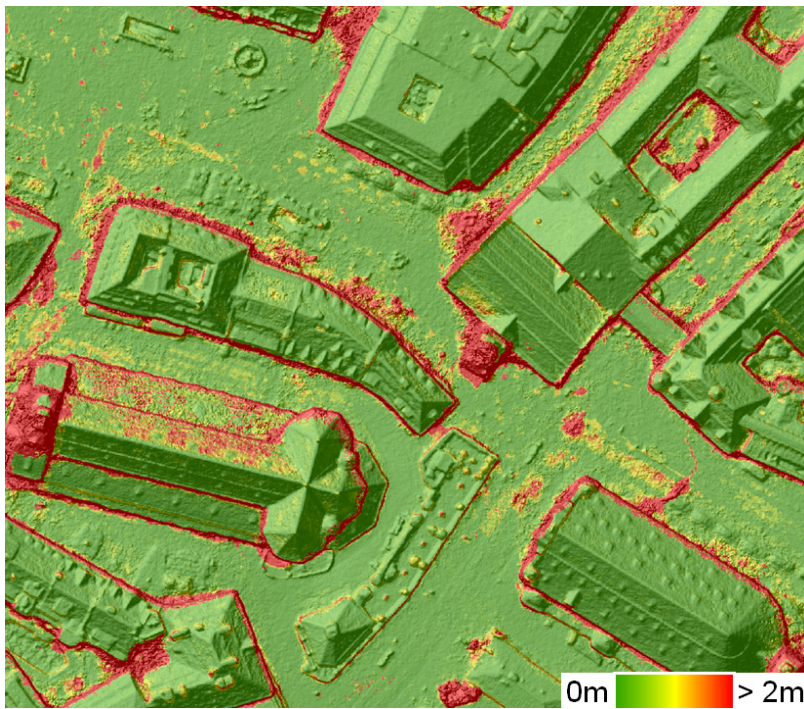


Figure 25: RMS differences for all solutions for München subsection.



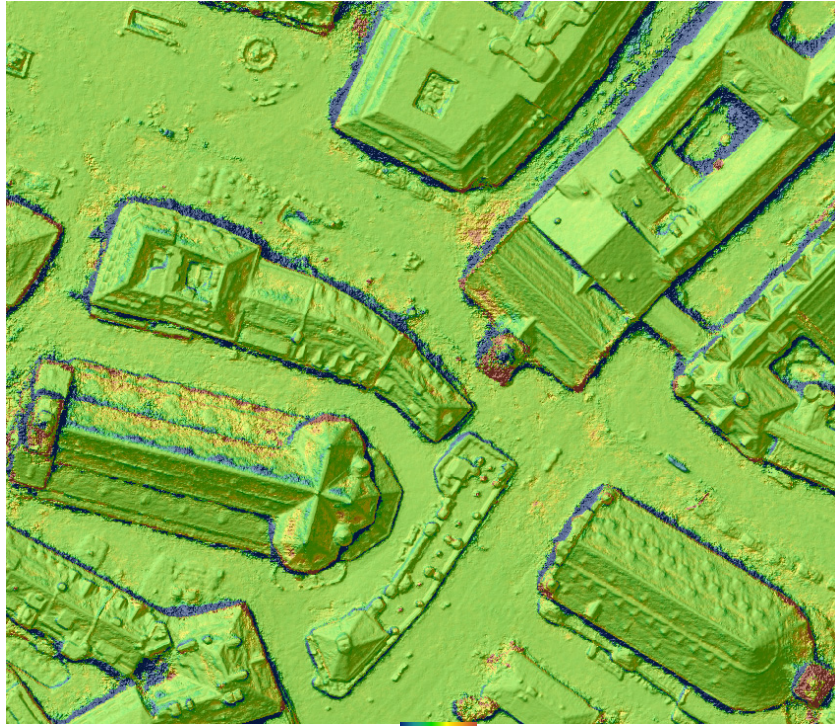



Figure 26: Match-T, DSM differences  $<-2m$    $>2m$

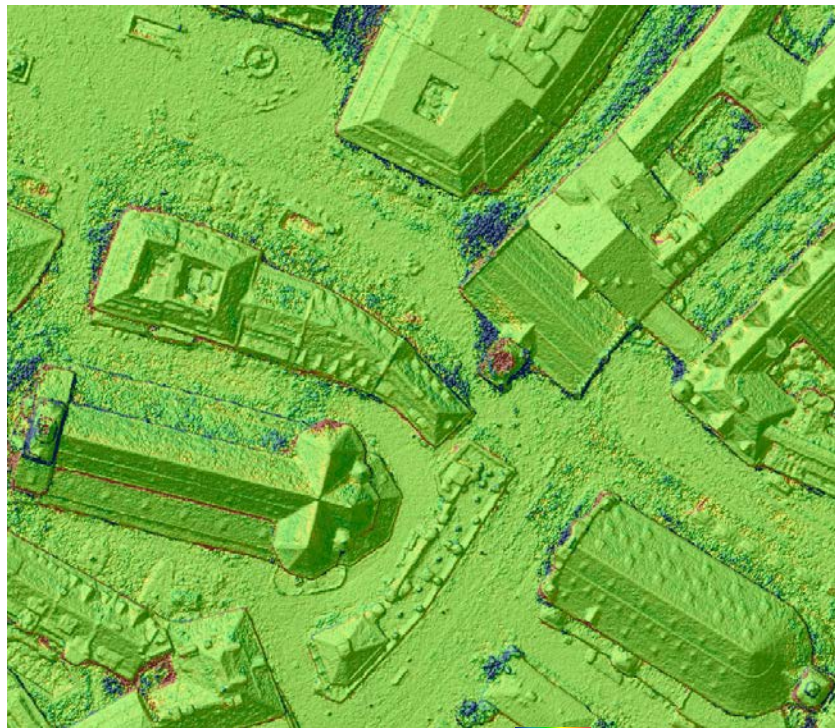


Figure 27: Joanneum research DSM differences  $<-2m$    $>2m$



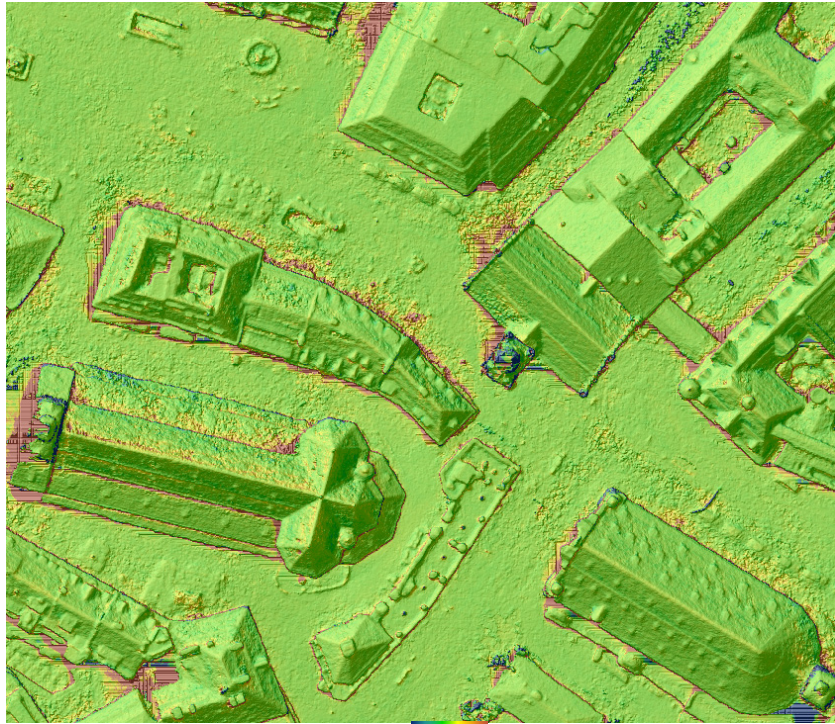



Figure 28: IfP-SURE DSM differences  $<-2\text{m}$    $>2\text{m}$

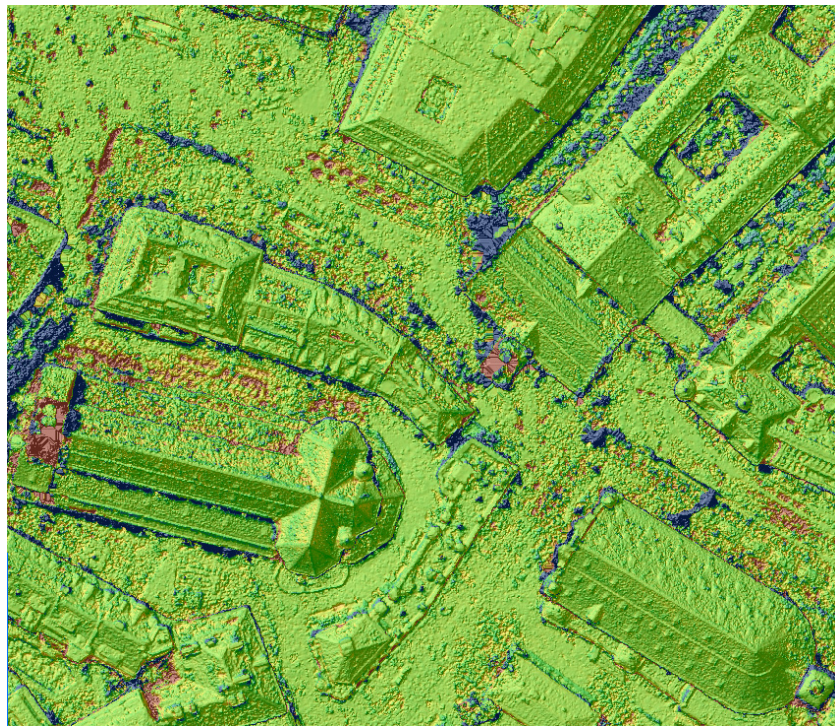


Figure 29: IGN MicMac DSM differences  $<-2\text{m}$    $>2\text{m}$



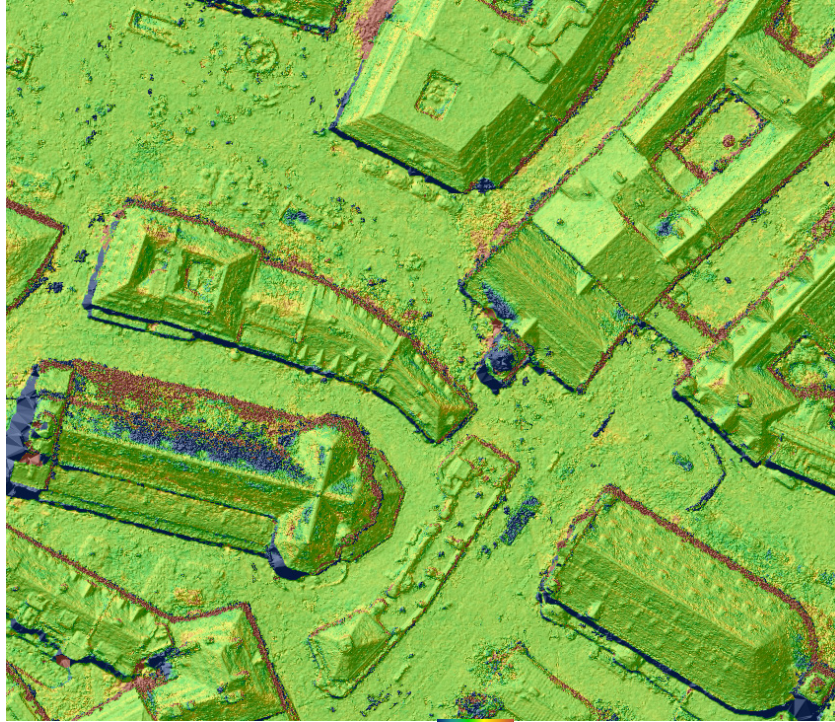



Figure 30: GeoSystems DSM differences  $<-2\text{m}$    $>2\text{m}$

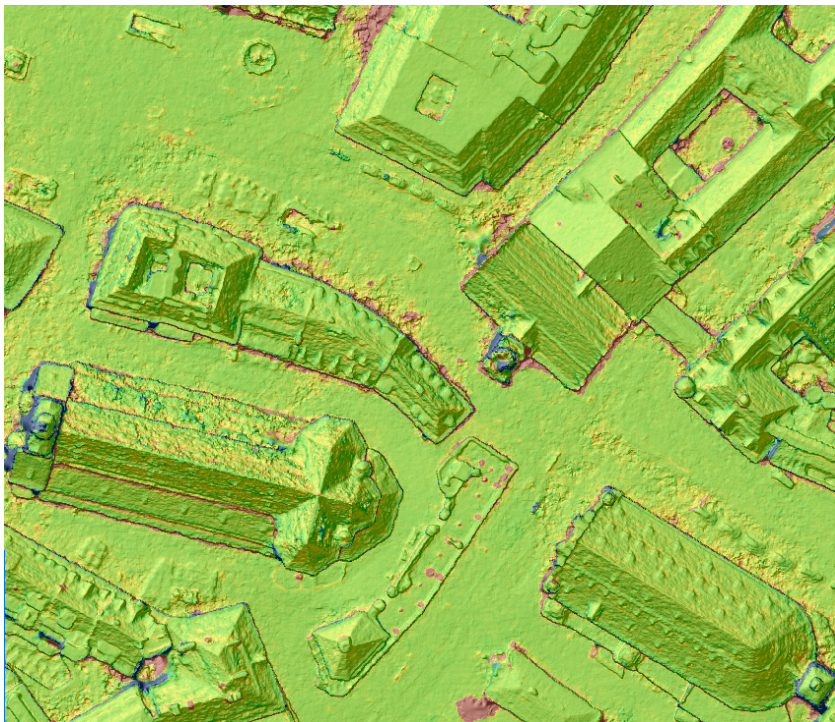



Figure 31: DLR DSM differences  $<-2\text{m}$    $>2\text{m}$



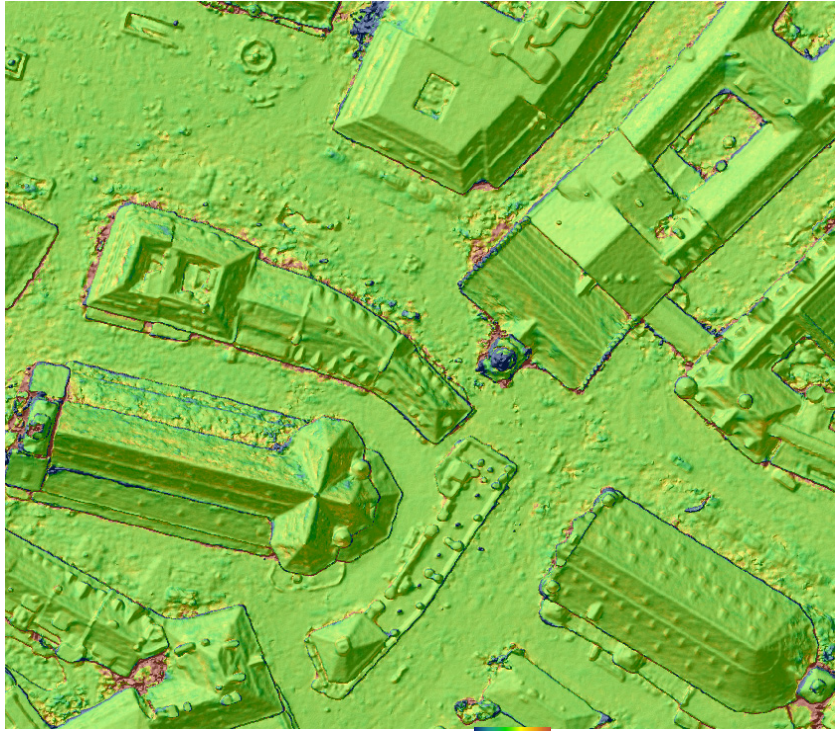


Figure 32: Astrium Pixel-Factory differences  $<-2m$    $>2m$

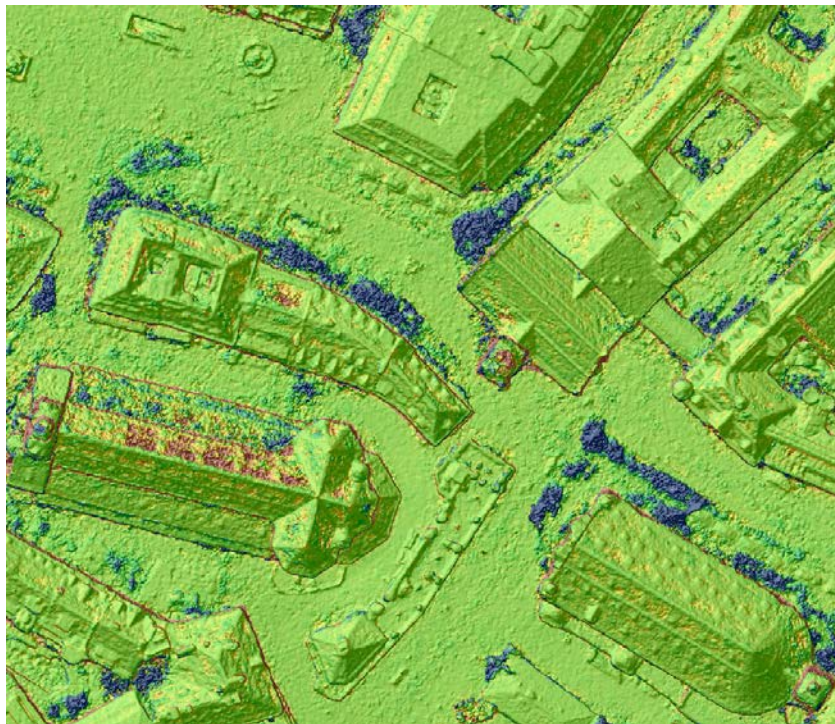


Figure 33: RMA differences  $<-2m$    $>2m$



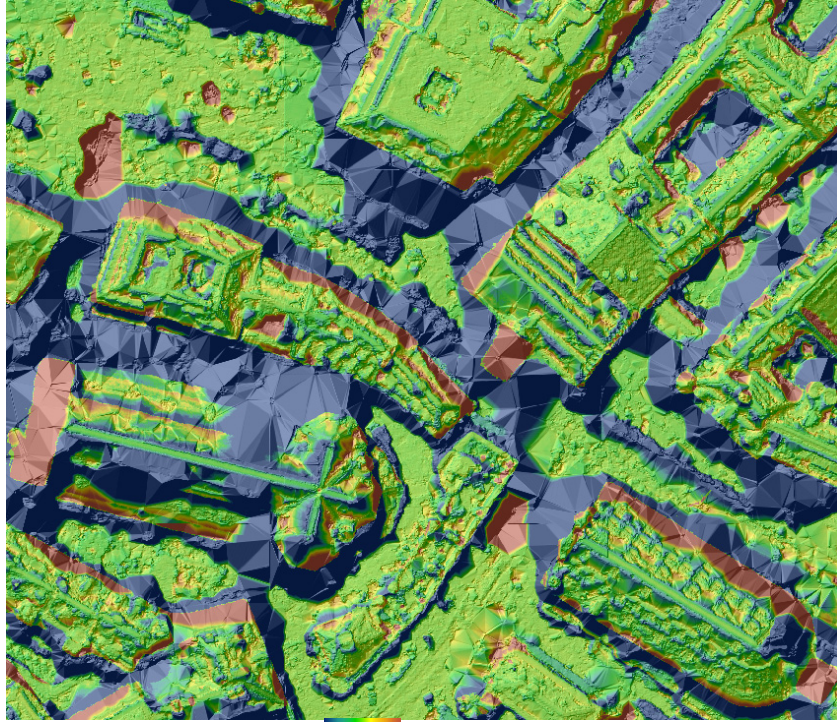


Figure 34: SocetSet differences <math>-2\text{m}</math> >math>2\text{m}</math>

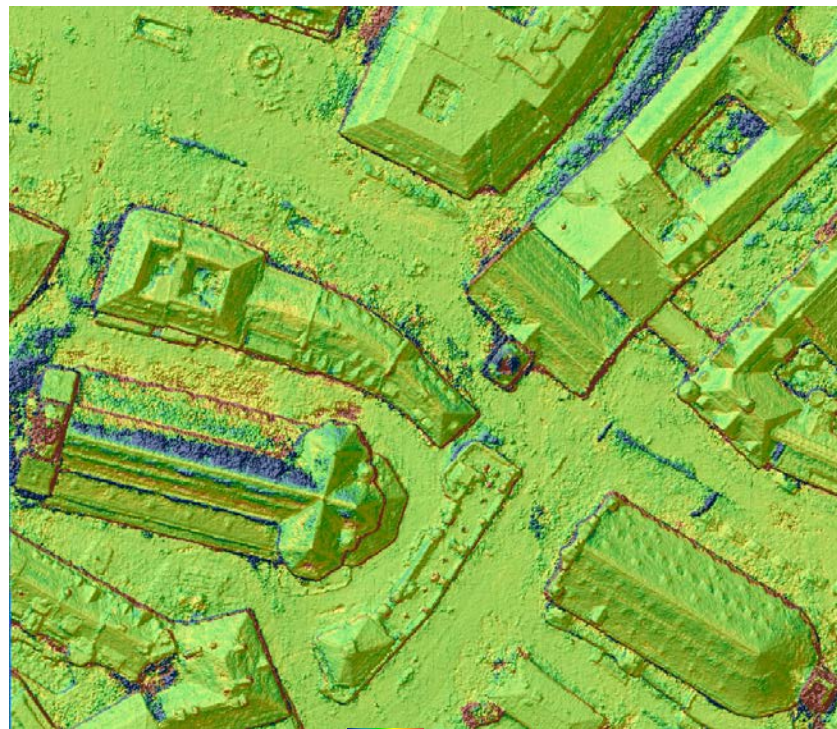


Figure 35: XProSGM differences <math>-2\text{m}</math> >math>2\text{m}</math>

Obviously, deviations between the respective DSMs occur at small details and steep edges in the vicinity of building borders. Furthermore, cast shadows seem to increase the noise level of the reconstructed surfaces. Elevation profiles extracted at such areas for further analysis are shown in Figure 36 to Figure 38 show. To improve the visibility of the results, the profiles from the SocetSet DSM, which suffers from large differences as already visible in Figure 34, are not included.

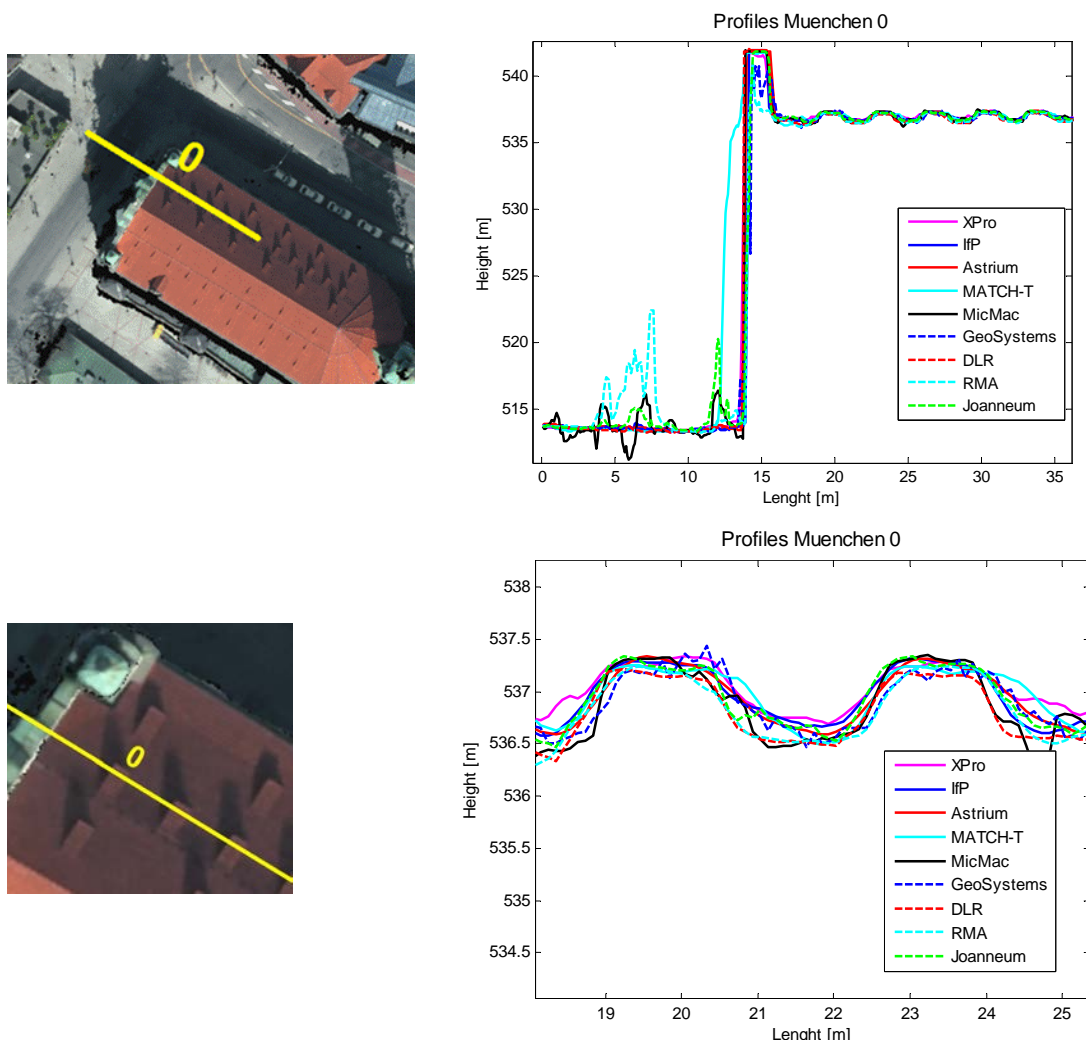


Figure 36: DSM-profile 0: Building and roof structures

Profile 0 depicted in Figure 36 starts on the ground surface covered with cast shadow, then pursues to a building with a distinct façade structure and finally continues on the top of the roof which includes some dormers. In the first part subject to the cast shadow the solutions from MicMac (solid black) and RMA (dashed light blue) appear relatively noisy. At the step edge of the façade Match-T (solid light blue) deviates from the other results. The bottom part of Figure 36 includes a close up view for the final part of profile 0 which covers two dormers. These structures apparently are correctly reconstructed by almost all solutions, the differences between the respective surfaces are at the 1 pixel level

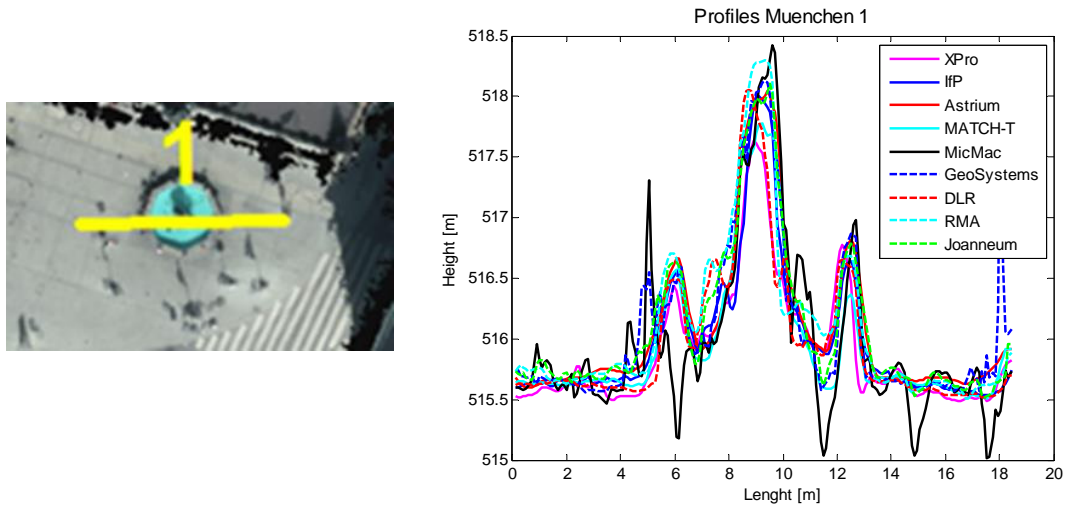


Figure 37: DSM-profile 1: Open place and fountain

Figure 37 shows the profile with label 1 extracted at an open place and contains a fountain. Apparently, the fine structures of this object, which are close to the GSD of 10cm are captured by almost all software solutions. Furthermore, for the low textured but well illuminated surface of the open place results in elevations differences between almost all solutions in the 1 pixel level. Only the DSM provided by MicMac seems to be relatively noisy.

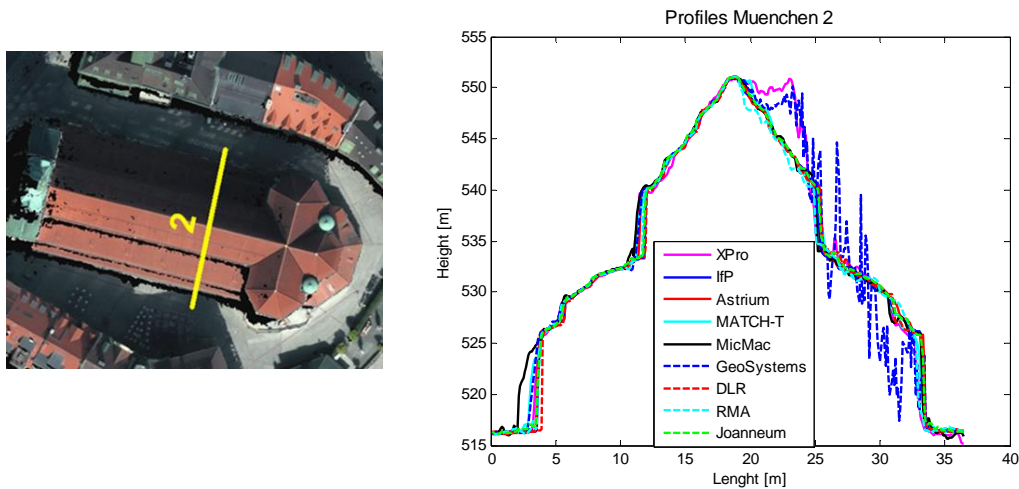


Figure 38: DSM-profile 2: Roof with cast shadow

The final example for the München test area, which includes a steep roof surface is depicted in Figure 38. Again, problems occur for some software systems at areas subject to cast shadow. While for these areas larger deviations occur for the DSM from GeoSystems (dashed blue) and XPro (solid magenta) the noise level increases for a number of software systems. Still, the geometric structure of the building is captured.



## 5 Conclusions

The results presented within the *Benchmark on Image Matching* clearly demonstrate the potential of software tools for detailed, reliable and accurate photogrammetric 3D data capture from airborne imagery. The aerial image blocks provided a suitable test-bed for software developers to demonstrate the state-of-the-art of their ongoing developments. Furthermore, the accompanying workshop helped potential users like National Mapping and Cadastral agencies (NMCAs) to understand the applicability of such tools for state-wide-generation of high quality DSMs. Obviously, the quality of image based surface reconstruction not only benefits from efficient stereo matching but takes advantage from large image overlaps. The resulting redundancy helps to eliminate erroneous matches and supports the generation of DSM at vertical accuracies close to the sub-pixel level. Most software systems show acceptable run-times even if a standard hardware environment is used. Data sets like the München city area at a size of 1.5kmx1.7km or the semi-rural Vaihingen/Enz area with moderate resolution and overlap at a size of 7.5kmx3.0km can be processed without problems to derive a DSM at grid intervals of 10cm and 20cm, respectively. Still, the benchmark also identified scenarios which can result in difficulties for image based surface reconstruction. DSM differences increased for fine object structures at a size close to the resolution of the available images. Furthermore, cast shadows induced decreasing DSM accuracies for some solutions. Thus, also further development of camera technique to improve the radiometry of the available images would be beneficial.

The area covering DSM differences and the extracted profiles helped to indicate the quality of photogrammetric surface reconstruction as available from the respective software systems. Nevertheless, a clear ranking was neither intended nor realized, also due to the fact that software development for image matching is still subject to a considerable momentum. Thus, further improvements can be expected both for matching accuracy and computational performance.

## Acknowledgement

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The most important prerequisite for realization of the benchmark on high density image matching for DSM computation is a sufficient number of participants volunteering for data processing. This work is especially acknowledged – without their valuable contribution such an initiative cannot be implemented.

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## Index Figure






















Figure 1: Vaihingen/Enz test area with ortho image and DSM. ....	118
Figure 2: Vaihingen/Enz: Image overlap (maximum nine-folded) with image footprints and camera stations. The area to be processed is depicted as light blue rectangle .....	118
Figure 3: München test area with DSM (left) and color-coded image overlap (maximum 15 folded) with image footprints, camera stations and area to be processed (right).....	119
Figure 4: Visualisation of test area München .....	120
Figure 6: Median DSM for all solutions of the Vaihingen/Enz subsection. ....	124
Figure 7: RMS differences for all solutions for a Vaihingen/Enz subsection. ....	124
Figure 8: Match-T, DSM differences <-2m  >2m .....	125
Figure 9: Joanneum DSM differences, <-2m  >2m.....	125
Figure 10: IfP Sure DSM differences, <-2m  >2m.....	126
Figure 11: IGN MicMac DSM differences, <-2m  >2m .....	126
Figure 12: GeoSystems DSM differences, <-2m  >2m.....	127
Figure 13: UltraMap DSM differences, <-2m  >2m.....	127
Figure 14: DLR-SGM DSM differences <-2m  >2m .....	128
Figure 15: Astrium Pixel-Factory, DSM differences <-2m  >2m .....	128
Figure 16: RMA, DSM differences <-2m  >2m.....	129
Figure 17: SocetSet, DSM differences <-2m  >2m .....	129
Figure 18: XProSGM, DSM differences <-2m  >2m.....	130
Figure 19: DSM-profile 0: Quarry 1.....	130
Figure 20: DSM-profile 1: Quarry 2 and vineyard.....	131
Figure 21: DSM-profile 2: Trees .....	132
Figure 22: DSM-profile 3: Building and water .....	132
Figure 23: Ortho image of München subsection with profile lines .....	133
Figure 24: Median DSM for all solutions of the München subsection.....	134
Figure 25: RMS differences for all solutions for München subsection.....	134
Figure 26: Match-T, DSM differences <-2m  >2m .....	135
Figure 27: Joanneum research DSM differences <-2m  >2m.....	135
Figure 28: IfP-SURE DSM differences <-2m  >2m.....	136
Figure 29: IGN MicMac DSM differences <-2m  >2m .....	136
Figure 30: GeoSystems DSM differences <-2m  >2m .....	137
Figure 31: DLR DSM differences <-2m  >2m.....	137

Figure 32 Astrium Pixel-Factory differences <-2m  >2m .....	138
Figure 33: RMA differences <-2m  >2m.....	138
Figure 34: SocetSet differences <-2m  >2m.....	139
Figure 35: XProSGM differences <-2m  >2m.....	139
Figure 36: DSM-profile 0: Building and roof structures .....	140
Figure 37: DSM-profile 1: Open place and fountain.....	141
Figure 38: DSM-profile 2: Roof with cast shadow.....	141

## LIST OF OEEPE/EuroSDR OFFICIAL PUBLICATIONS

State – March 2013

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