Comparison and fusion of DEM derived from SPOT-5 HRS and SRTM data and estimation of forest heights

Peter Reinartz, Rupert Müller, Danielle Hoja, Manfred Lehner, Manfred Schroeder
German Aerospace Center (DLR), Remote Sensing Technology Institute, Wessling, Germany

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ABSTRACT: There are several ways to produce digital elevation models (DEM) from spaceborne satellite data. In this study, two techniques and their results will be compared: DEM derivation with optical stereo data acquired with the French SPOT-5 HRS instrument and DEM derived from C-band and X-band radar data acquired during the SRTM mission. A comparison of the accuracy is given for different landscapes and land use classes using reference DEM from laser scanner data and aerial photography. Both systems show advantages and disadvantages but have similar accuracy values in comparison to a reference DEM, in both cases the resulting DEM is actually a mixture of a digital surface model (DSM) and a digital terrain model (DTM) since the reflection/back scatter results from a mixture of different targets in each resolution cell. Therefore in a forest area neither the forest canopy nor the terrain height itself is modeled. Additionally a DEM fusion, utilizing height error maps for each DEM, is performed. It is shown that a fusion of the DEM derived from optical and radar data leads to higher accuracies in nearly all cases. A comparison of the space borne DEM with the reference DEM shows a higher absolute difference in forest areas than in agricultural regions. The absolute difference gives an estimation of the canopy height of the trees, although the scattering process (in the radar case) and the reflection and matching techniques (in the optical case) cause lower values than the real height of the trees. It is shown whether an estimation of the real mean tree height is possible with the additional knowledge of tree parameters like species and density. Results are compared for both DEM generation techniques to the data received from in-situ measurements.

1 INTRODUCTION

Mainly two completely different data acquisition methods from space allow the derivation of digital elevation models (DEM) in a quality of DTED Level 2: optical along track stereo imaging (e.g. SPOT5, ASTER) and radar interferometrie (InSAR, e.g. SRTM X- and C-band, ERS-Tandem). The quality of the derived DSM varies in dependence of the steepness of the terrain and the land cover classes. For flat terrain or moderate hilly landscape, the height accuracy which can be achieved is in the order of 5 to 10 meters in height for all mentioned sensors (Rabus et al. 2003, Jacobsen 2004, Bouillon et al. 2003). Since both techniques have advantages and disadvantages it is interesting to look at the accuracies of the derived DSM in dependence of the above mentioned landscape parts and to see whether a fusion of the independently derived DEM leads to improved results. For a reasonable fusion of DEM, a height error map for each DEM giving the local estimation of accuracy depending on the production process is obligatory.

The derivation of digital elevation models (DEM) from optical along track stereo data from space has up to now only been possible with the German MOMS-2P camera system (Müller et al. 2001) and the Japanese/American ASTER sensor on TERRA (Toutin et al. 2001). Both of them have lower resolution (15-18 meter pixel size) than the new HRS sensor on SPOT-5. HRS produces image stereo pairs with two optics looking forward and backward (±20 degrees). The camera has a spatial resolution of 10 meter across track and along track, but a ground sampling distance of about 5 m along track for obtaining higher resolution of the parallaxes for the DEM generation. The swath of the HRS is 120 km (12000 CCD elements) and one acquisition sequence extends 600 km along track. After the ISPRS Commission I Symposium in Denver in November 2002, the HRS Scientific Assessment Program has been established. This program gave the user community the opportunity to test HRS data, which are usually not available to the public, for generating DEM and for comparison with other DEM generation methods. For the investigations 9 test areas around the world with corresponding PIs and co-investigators have been selected (Baudoin 2004). Two of these areas are investigated in this paper.

During the SRTM mission in February 2000 nearly all the land mass between 56° south and 60° north latitude has been covered. Since the German/Italian X-band antenna acquired only a swath of 45 km it could not cover the whole area, while the American C-band system covered 94.6% of the land mass with a swath of 225 km; approx. 50% of the area was covered three times. The X-band data with a wavelength of approx. 3 cm penetrates vegetation only little, while it is expected that the C-band data with a wavelength of about 5.6 cm will penetrate somewhat more into the canopy. The C-band information is only available with a spacing of 3 arcsec (~90 m) while the X-band DSM is available with a 1 arcsec spacing.

2 TEST AREAS, SPACE DATA AND GROUND REFERENCE DATA

There are two test areas chosen, where all three data sets are available. The first test area is a region of about 40 x 50 km² in the southeastern part of Bavaria. The elevations range from 400 to 2000 meters in a mostly hilly, post-glacial landscape including some lakes and also mountains of the German Alps. This selection allows the comparison of DEM for different land surface shapes and includes many medium size forest areas with different tree species.

The ground reference data (DTM) selected for this test area are the following:

- Four regions have a grid spacing of 5 meters and an overall size of about 5 km x 5 km, derived from airborne laser scanning. The height accuracy is better than 0.5 m.
- 81 GCP (fix points) with accuracy of 0.1 m

The second test area is located in Catalonia (Spain) and includes the city of Barcelona (overall size: 60 km x 60 km). The ground reference data for the Catalonia area, with similar landscape, but including the Mediterranean coast are the following:

- 32 color orthoimages (1:5000) with pixel size of 0.5 meter and accuracy better than 1 pixel (1σ)
- DEM with pixel spacing 15.0 meter and orthometric height accuracy of 1.1 m (1σ)

The optical image data which have been provided by SPOT IMAGE in the framework of the SPOT HRS Scientific Assessment Program of CNES and ISPRS in 2003 contain the following parts:

- Sets of 8 bit panchromatic image data (size 12000 x 12000 pixel = 120 km across x 60 km along track) of the Bavarian and Catalonian test area from two viewing directions in tiff-format
- In the Catalonia area as well HMA and HMB data: 5 m x 5 m resolution panchromatic nadir looking channels of part of the test site (size 12000 x 12000 pixel = 60 km across x 60 km along track)

- XML-files containing all additional information regarding time synchronization, position (DORIS), attitude (star sensors and gyros), interior orientation
- Text files containing information on the delivered data.

The data of Bavaria have been acquired on October 1, 2002 with a sun elevation of 38º and nearly no clouds. The data of Catalonia have been acquired on October 15, 2002 with a sun elevation of 39º and no clouds. The radiometric quality of the Catalonia images is superior to the Bavarian imagery probably due to better atmospheric conditions.

The radar images have been acquired during the SRTM mission in February 2000. Both data sets, the German/Italian X-band DEM and the American C-band DEM have been used for comparison and fusion.

3 DEM GENERATION

The DEM from the SPOT stereo data have been derived using DLR software. Details on this software are described in Lehner et al. 1992. It relies on a 7-step image resolution pyramid and applies intensity matching in two forms: normalized correlation coefficient for pixel accuracy and subsequent local least squares matching (LLSQM) for refinement to sub-pixel accuracy (for mass points 0.1 to 0.3 pixel standard deviation). Interest points are generated with the Förstner operator and the homologous points are searched for in the other image. Only points with high correlation and quality figure are selected as tie points if bundle adjustment is applied and a less stringent criterion is valid for the usage as seed points for the subsequent Otto-Chau region growing procedure for dense matching (Heipke et al 1996). This local least squares matching starts with template matrices of 11 x 11 pixels around the seed points with a step of 1 to 3 pixels in each direction. For cross checking a backward match is performed for all points found.

Having the mass points from the matching process as well as the exterior and interior orientation of the camera system, improved by ground control points, the object space coordinates can be calculated using forward intersection. This is done by least squares adjustment for the intersection of the imaging rays. The irregular distribution of points in object space after the forward intersection is regularized into an equidistant grid of 15 m (Catalonia) and 25 m (Bavaria) spacing. The interpolation process is performed by a moving plane algorithm (Linder 1999). The resulting DEM, which is something between a surface and a terrain model, is compared to the reference DEM, which is purely a terrain model. Therefore a distinct difference is expected e.g. in forest areas. First investigations on these data sets have been carried out in (Reinartz et al 2004 and Müller et al 2004)

The SRTM X-band DEM data have been processed by DLR standard processing (Rabus et al 2003), the area in Catalonia is covered by an ascending and a descending data take, while the Bavarian test site is only covered by one data take. The SRTM C-band DEM data have been downloaded from the US ftp site.

4 DEM COMPARISON AND DEM FUSION IN THE CATALONIA TEST SITE

For the Catalonia area a comparison of the three DEM (C-band=C, X-band=X, SPOT-5=5) and the possible fused DEM (CX, C5, X5, CX5) has been performed. For a correct fusion at first the mean values of both DEM in the overlapping areas are calculated and a possible offset is taken into account for the fusion. The first input DEM is taken as reference height. To be able to take into account the generation process for each DEM, the fusion has been accomplished with the support of height error maps. In the SRTM case this layer is produced on a routine base by using features of coherence and density of residuals in the DEM generation process. For the optical data, a height error map was generated by using the mean standard deviation as a lower limit and the density of the matched points after the region growing process as a criterion of the reliability of the DEM raster-interpolation. Figure 1 shows a comparison of the three height error maps. They represent the local error estimation in meters. The structure of the three layers look quite different, which is due to the above mentioned difference in DEM production and error possibilities: The height error map for C-band DEM exhibits a mean of higher error values, while the X-band DEM shows low values in moderate terrain and high values in mountainous regions and SPOT-5 DEM also has generally lower values but some higher error probability in forest and low contrast regions. The resulting height error map in the fused DEM leads to lower values of the mean error probability in the whole region because of the different local distribution of errors of the different processing techniques. Table 1 shows the mean differences as well as standard deviation and min/max values of the differences for three areas in and around Barcelona.

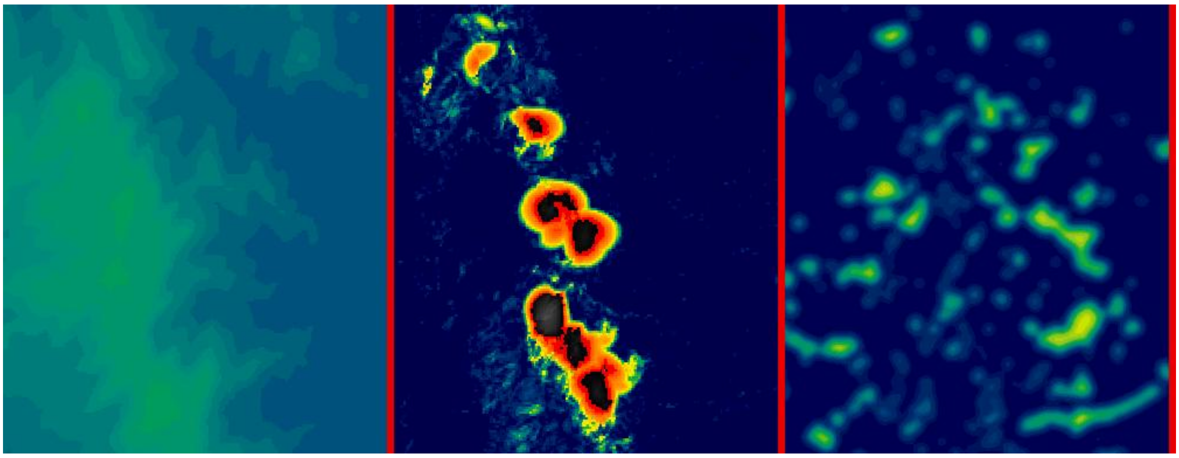


Figure 1: Height error maps of three DEM data: SRTM C-band, SRTM X-band, SPOT-5 HRS (blue: low-, green: medium-, yellow: high-, red: very high error probability)

Table 1: Area-wise comparison of height of SPOT-5/SRTM-X and SRTM-C-band DSM to the reference DTM

	Fields			***Suburbs of Barcelona***			***Forest***		
	mean [m]	**σ [m]**	**min/ max[m]**	**mean [m]**	**σ [m]**	**min/ max[m]**	**mean [m]**	**σ [m]**	**min/ max[m]**
C-band	-1,6	9,8	-32/25	0,4	2,8	-17/9	3,3	12,3	-53/45
X-band	0,3	5,6	-29/47	4,1	4,3	-31/23	10,0	10,5	-40/51
Spot5	0,1	5,1	-43/42	1,1	3,3	-14/27	3,1	8,9	-53/55
CX	-2,9	6,5	-25/31	0,2	3,3	-14/15	5,8	10,1	-40/42
C5	1,0	5,3	-18/19	0,8	2,6	-11/14	3,0	8,4	-35/39
X5	2,3	4,8	-13/19	3,6	3,2	-11/23	8,4	8,8	-31/44
CX5	0,5	4,9	-15/15	0,9	3,0	-11/15	5,7	8,6	-31/39

Table 1 shows several effects which are generated by the fusion process. The areas which were investigated represent typical classes of land use and allow an easier interpretation of the effects which can be found for the whole fused area as well. The mean value, which is a kind of bias between the three differently generated DEM is generally low and shows only higher values in the case of forest areas. The reason why the values are somewhat higher in the case of SRTM X-band data is that these values represent more a DSM than it is the case for C-band (also lower geometric resolution!) and SPOT-5. The radar backscatter from buildings and trees introduces typically more height values than the matching with kernels of about 11 by 11 pixels in the case of SPOT-5 (see also the chapter on forest heights in Bavaria). During the fusion process one of the DSM is introduced as correct in the sense of the mean height for the whole area, therefore it may happen that mean values in comparison to the reference DTM vary a little for the areas listed in table 1. The area based standard deviations show expected values for the different classes. The C-band DSM shows the highest values while the SPOT-5 DSM shows the lowest. This tendency is true for all areas investigated and especially larger for mountainous areas (Reinartz et al 2004). The standard deviations decrease through the fusion process in nearly all cases, which gives rise to the assumption that the fusion of this kind of DSM improves the overall accuracy. Figure 2 shows the decrease of the standard deviations in using different DSM and their fused products. The improvement is visible although not very high. It becomes more evident when the min/max values of the DEM deviations are compared (see table 1). These values are reduced drastically by the fusion process, especially when the SPOT-5 data are involved. The effect of improvement using all three DSM (CX5) is not very obvious in comparison to the combination C5 or X5.

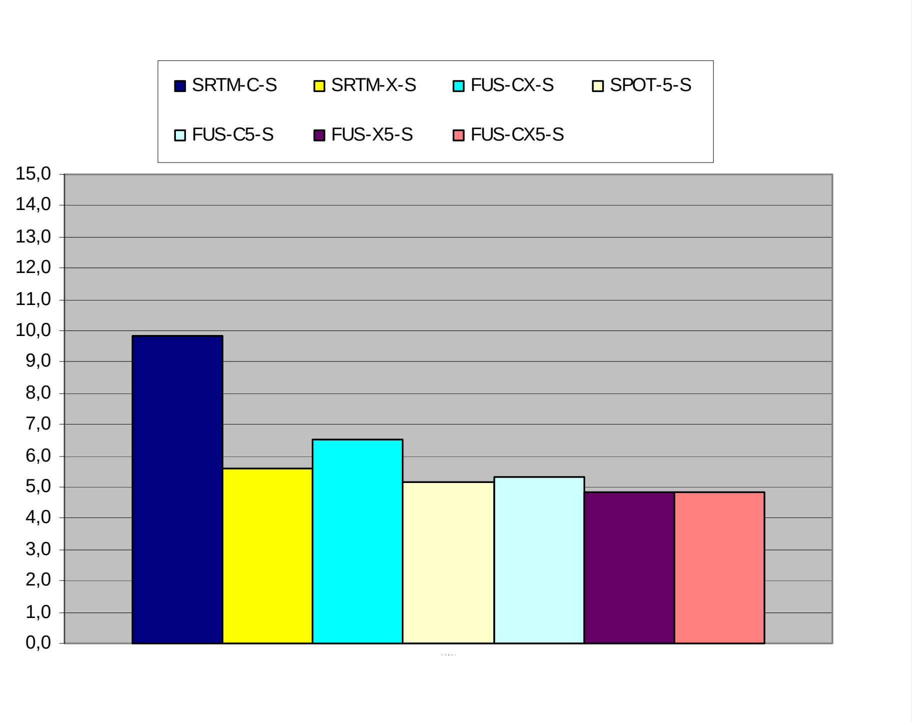
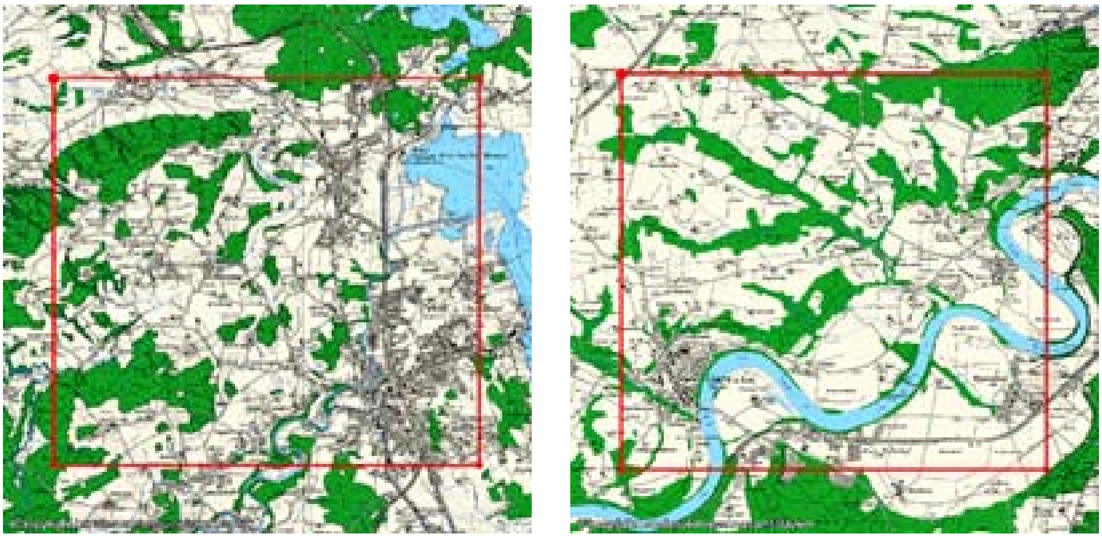


Figure 2: Mean accuracy (σ) for several DEM and fused DEM in comparison to the reference DEM

5 DEM FOREST HEIGHTS COMPARISON IN THE BAVARIAN TEST SITE

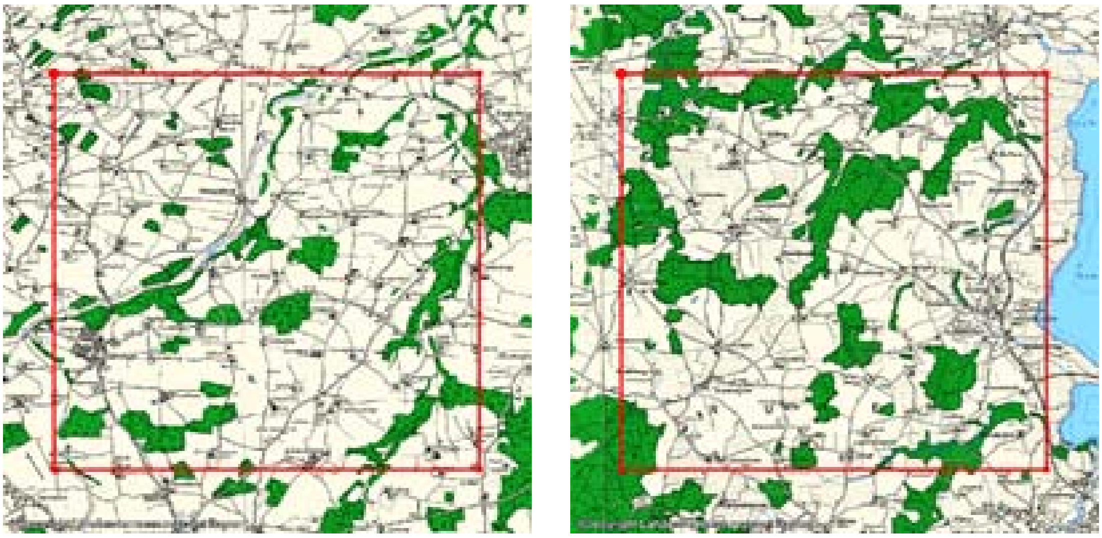
In the test area of Bavaria four reference DEM were available for testing the accuracy (see chapter 2). The comparison of the three differently generated DSM to the reference DTM is concentrating in this chapter on an analysis of extracting forest canopy heights. The four test areas are shown in Figure 3, each of them exhibits several forest areas which are large enough to be investigated as a contiguous area to estimate mean canopy heights. The forest areas have been selected by three methods:

- Automatic classification (Maximum-Likelihood classifier)
- CORINE database (geometric resolution: 100 m x 100 m)
- Manual mask generation



Test area 01: Prien

Test area 02: Gars



Test area 03: Peterskirchen

Test area 04: Taching

Figure 3: Four test areas in Bavaria for extracting forest canopy heights.

The first two lead to area based mean results of different forest types and heights and give therefore only tendencies for the quality of the three DEM, while the last leads to detailed results also for small forest areas. The results for the last method are also compared to the canopy height (mean heights of an area) and canopy density given by in-situ measurements. Table 2 shows the result of mean height differences and their standard deviations. It is obvious that mean height differences (bias) are very low for all areas outside forests, while forest mean heights are mostly above 10 meters for all DEM (especially high for X-band); they are about 30% lower for the filtered SPOT-5 DEM. The standard deviations are about twice as high for forest areas then for non-forest areas. This is expected since the places of signal reflection vary much more for forest areas than for fields or meadows.

Table 2: Comparison of height differences and standard deviations for SRTM C-band, X-band and SPOT-DEM with the reference DEM

Reference area	Mean height difference (non-forest) [m]			Mean height difference (forest) [m]		
	C-band	X-band	SPOT5	C-band	X-band	SPOT5 / Filter
DEM-01, Prien	0.0	-	1.4	10.8	-	11.9 / 7.8
DEM-02, Gars	-1.5	-	0.3	8.2	-	13.0 / 9.6
DEM-03, Peterskirchen	0.6	-	0.6	10.7	-	10.5 / 7.8
DEM-04, Taching	-0.6	-0.4	0.1	13.1	16.3	11.9 / 6.4

Reference area	σ (non-forest) [m]			σ (forest) [m]		
	C-band	X-band	SPOT5	C-band	X-band	SPOT5 / Filter
DEM-01, Prien	4.1	-	4.0	10.6	-	8.5 / 7.1
DEM-02, Gars	4.8	-	5.0	11.0	-	10.2 / 10.0
DEM-03, Peterskirchen	3.5	-	5.5	6.6	-	6.5 / 6.4
DEM-04, Taching	6.0	5.7	6.1	10.0	10.2	9.6 / 9.7

The result for the CORINE classification (table 3) is very similar although in this case the classification with a pixel size of 100 m x 100 m is very coarse. The standard deviations are a little lower probably because more non-forest area is involved in the calculations. This means that the CORINE database is suitable for a coarse estimation of forest heights.

Table 3: Comparison of height differences and standard deviations for SRTM C-band, X-band and SPOT-DEM with the reference DEM (CORINE-classification)

Reference area	Mean height difference (forest) [m]			σ (forest) [m]		
	C-band	X-band	SPOT5-Filt	C-band	X-band	SPOT5-Filt
DEM-04, Taching	13.4	15.9	7.1	7.3	9.5	7.7

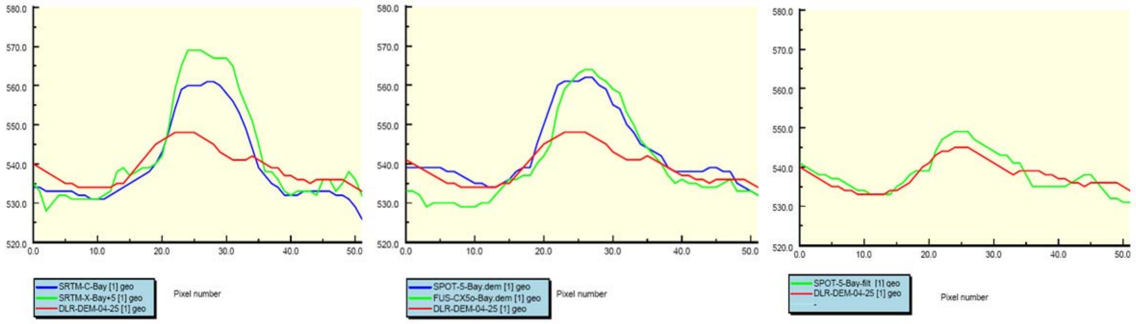


Figure 4: Profiles of a forest stand in left: SRTM DSM (X: green, C: blue), middle: SPOT-5 (blue) and fused DSM: CX5 (green), right: SPOT-5 filtered DEM, all in comparison to the reference DTM derived from laser scanning (red)

For a more detailed evaluation of forest heights, image masks have been generated manually to be able to compare derived heights for single forest stands. 28 stands have been selected, which cover several types of tree species, heights and densities. Figure 4 shows typical profiles of a small forest stand in the different DSM and the reference DTM. It can be seen clearly that the highest values (with the steepest rise at the forest borders) result from the X-band data, while the SPOT data exhibit the lowest values. Using a special filter during the DEM derivation process, described in (Jacobsen 2004) these forest heights can be even reduced to achieve a DEM closer to the DTM (see also Fig 4c).

The results for all stands of test area 04 are shown in table 4 for each produced single DEM. The correlation to the actual mean forest heights is not very high which is due to the fact that all forest areas are not really homogeneous in their tree heights and also in the composition of their tree species. Nevertheless several tendencies can be seen clearly in table 4:

- The derived heights are lower than the in-situ measured heights (tree tops), which can easily be explained by thinking about the scattering process which not only takes place at the top of the trees;
- The forest heights are estimated slightly higher in X-band than in C-band data (about 10-20%), which is explained by the theory of deeper penetration of C-band data and/or coarser horizontal resolution of the latter;
- The forest height is estimated lower with the optical SPOT-5 data in comparison to the InSAR derived DEM (about 20-50%), this can be due to the reflectance properties of forests which is a mixture of several height levels and partly because of the matching process and kernel size for the correlation windows;
- The filter for the SPOT-5 data introduces different effects, depending on the forest stand: while some stands nearly vanish (in mean height), others have still quite high values.

Table 4: Comparison of forest heights with in-situ measurements for test area 04, Taching

Forest area	C-band	X-band	SPOT-5	SPOT-5 filter	In situ measured mean height
1	16,2	17,5	13,2	9,8	19
2	20,1	21,0	15,8	-1,1	27
3	17,1	21,6	13,6	6,6	30
4	20,1	20,7	10,6	3,7	28
5	22,0	23,5	15,6	9,9	27
6	17,2	20,6	16,0	9,0	29
7	20,9	23,4	12,8	4,0	25
8	20,1	24,1	20,4	11,4	25
9	21,9	24,2	14,8	8,5	30
10	20,0	21,0	19,4	16,5	25
11	19,9	25,9	14,1	6,0	25

6 CONCLUSION

It could be shown that a fusion of DEM from different sources (optics and radar) including their accuracy layers leads to improved results in comparison to the reference DEM. Especially the highest deviations are reduced when using the fused DEM derived from an optical and a radar data set. This argues for the complimentary nature of the different DEM generation procedures and the advantage of the combined usage of the two techniques.

The evaluation of forest heights from the different DSM leads to an underestimation of the actual heights in all cases. Since this underestimation has a regular behavior, a rough estimation of the forest height can be performed by knowing the sources of the DSM (radar/optical). DSM derived from radar data exhibit higher mean values in forest stands than in the DSM derived from SPOT-5 HRS data. Accurate values of forest heights cannot be given in all cases since the dependence on tree density, tree species and tree mixture is quite high. Further investigations will try to quantify these dependencies to allow a more precise estimation of the forest heights for different cases.

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