DEM Generation Using Optical / Radar Satellite Images - A Comparative Study

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Abstract: *A digital elevation model (DEM) is the most basic and interesting geographical data type. Different techniques are used for the acquisition of DEM source data: aerial and satellite photogrammetry, radargrammetry, SAR interferometry, airborne laser scanning (LIDAR), cartographic digitization of the existing maps, traditional and modern surveying techniques. Today, DEM generation by means of optical satellite images is becoming a very advantageous method: it offers updated information, large area coverage, quick data access and it is cost effective. Also, interferometry is widely used for DEM creation, especially with the launch of very high resolution radar satellites like ALOS (2006) and TerraSAR-X (2007). The article presents the main sources of data for DEM generation and a comparative study: DEM generated by SPOT 5 HRS stereo images versus DEM generated by Interferometric SAR (InSAR) based on the Shuttle Radar Topography Mission (SRTM) height model.*

Keywords: *digital elevation model, optical/radar satellite images, comparative study.*

1. Introduction

"A **d**igital **t**errain **m**odel (DTM) is simply a statistical representation of the continuous surface of the ground by a large number of selected points with known X, Y, Z coordinates in an arbitrary coordinate field." This definition was given by Miller and Laflamme, two engineers of Massachusetts Institute of Technology, which introduced the concept of digital terrain model in 1958. Since then new techniques of data acquisition and processing have been developed and new types of DTM applications have come into sight: from highway and railway design to agriculture management, flight simulation, flood monitoring and many more.

2. Data Sources for DEM Generation

A **d**igital **e**levation **m**odel (DEM) is usually used to refer to any digital representation of a topographic surface and describes height above sea level being from this point of view the most accurate material on elevations. The points that define a DEM are describing the bare soil. The data used for digital terrain modeling can be obtained using different techniques: photogrammetry (aerial and satellite images), radargrammetry, SAR interferometry, airborne laser scanning (LIDAR), cartographic digitization of the existing maps and surveying techniques.

Aerial or space images are considered to be the most effective method for producing and updating topographic maps (Li and al. 2005). Based upon a pair of stereo images (taken over the same area from slightly different positions), the 3D model of the terrain can be reconstructed in the overlapping area of the two images. Satellite images used for the same purpose have the advantage of large area coverage. Also, the resolution of these images is permanently increased.

DEM generation using images acquired by radar satellite sensors can be accomplished through radargrammetry or SAR interferometry. The principles of radargrammetry are similar to the ones of photogrammetry: two radar images are taken from two different directions with a certain degree of overlap. For example, the images acquired from ascending/descending orbits could present significant different radiometry that can make the visual or digital interpretation very difficult. In mountainous areas, these differences can become more accentuated due to view shadows found on opposite sites. The radar images used in radargrammetry contain only the amplitude information. On the other hand, SAR interferometry is using the phase information of the radar images. In the specialty literature, it is considered that the interferometric DEM has better spatial resolution and superior accuracy, especially in rolling or plain areas, in comparison with the DEM generated by means of radargrammetry (Crosetto et al. 2000).

LIDAR is an active system. Its altimetric accuracy is 10-60cm, while planimetric accuracy is 0.1- 3m. The point spacing is between 0.1 and 20 points per square meter. The airborne laser scanning represents a very accurate and rapid technique for data acquisition, but is very expensive.

The DEM obtained by means of cartographic digitization is determined by the quality of data contained by maps. The accuracy of the DEM generated by digitization depends on the density of contour lines and the accuracy of the contour lines themselves. The height accuracy of any point interpolated from contour lines should be about 1/2 to 1/3 of the contour interval (Li and al. 2005). Traditional and GPS surveying offer high accuracy (millimeter-level), but these techniques are suitable only for small areas.

3. Satellite Missions

3.1. SPOT 5 HRS

The HRS (High Resolution Stereoscopic) instrument on board of the satellite SPOT 5 is especially designed for the generation of DEMs from along-track stereo imagery. The stereoscopic imaging of this system has the height to base relation of 1.2 and just 90 seconds time interval of taking corresponding images. By this reason there is reliable guarantee that there are the same illumination conditions, no change of the object and the same atmospheric situation.

At the time of the same passage of the satellite the forward-looking sensor acquires images of the ground at a viewing angle of 20° ahead of the vertical and after one minute and a half the backward-looking sensor achieves images of the same portion of the ground at an angle of 20° behind the vertical (figure 1). The nadir angle of 20° corresponds to 22.5° incidence angle on account of the earth curvature.

Fig. 1 SPOT HRS camera system

That means the height to base relation has the optimal value of 1.2 for generating digital elevation models. The height to base relation represents the angle between the intersecting rays and the achieved vertical accuracy is depending upon this parameter.

The HRS camera system includes two combined CCD-line cameras. Each CCD-line has 12000 pixels and the pixel size on the ground is of 5m in orbit and 10m across the orbit. The height determination is better because it depends upon the pixel size in orbit direction. The standard scene size is covered by this stereoscopic arrangement has the size of 120 km x 60 km. The spectral domain of the HRS is the panchromatic band (0.49-0.69µm).

3.2. SRTM-InSAR

Shuttle Radar Topography Mission (SRTM) consists of a specially modified Synthetic Aperture Radar (SAR) system that flew onboard the Space Shuttle Endeavour which was launched into space on the 11th of February 2000. During an 11-day mission SRTM had the goal to obtain data in order to generate the most complete high-resolution digital topographic database of the Earth.

SRTM InSAR was using two radar systems with different wavelengths. One was the C-band radar system operated by the USA having a wavelength λ=5.6cm and the other was the X-band radar system with λ=3cm operated by Germany and Italy.

The radar interferometry technique implies the acquirement of two radar images from slightly different locations in order to calculate the surface elevation. The two antenna systems of the SRTM which were separated by a fixed distance of 60 meters (the mast) were collecting two radar data sets. The main antenna was operated in active and passive mode because it transmitted and received signals while the outboard antenna was just passive. The main antenna illuminated a portion of the Earth´s surface with a pulse of 1/10 of a microsecond using a beam of radar waves. This beam of radar waves hit the Earth surface and the rays that are scattered in different directions were collected by the two antennas (figure 2). The X-band data set can be bought with a point spacing of 1 arc second (≈30m) while the C-band data are available free of charge with a reduced spacing of only 3 arc seconds (≈ 90m).

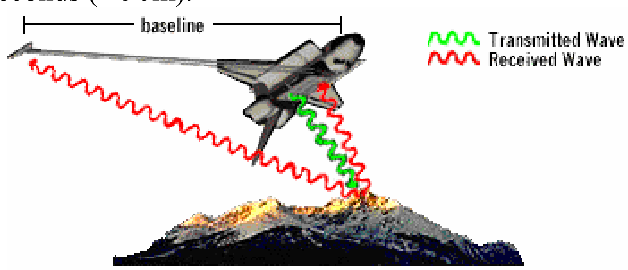


Fig. 2 Radar signals being transmitted and received in the SRTM mission

3.3. Other Relevant Satellite Missions

Today, DEM generation by means of optical satellite images is becoming a very advantageous method, it offers updated information, large area coverage, fast data access and it is cost effective.

Some satellite platforms launched in the past years have stereoscopic capabilities and increased spatial resolution. Among these platforms, there are: QuickBird, Ikonos, Eros A, OrbView, Cartosat-1, Cartosat-2, Kompsat-2, Kompsat-3, Formosat, Aster and WorldView-1. The very flexible satellites, like Ikonos, QuickBird, OrbView, Cartosat-2 and WorldView-1, are able to generate stereo models from the same orbit by fast rotation of the satellite, while Cartosat-1, like SPOT-5 HRS, is equipped with 2 sensors and ALOS-PRISM even with 3 sensors for permanent stereoscopic coverage.

Also, DEM generated by interferometry is gaining more and more ground due to the high and very high resolution satellite systems launched recently, like: ALOS (spatial resolution 2.5m, launched by Japan in 2006), TerraSAR-X (spatial resolution 1m, launched by Germany in June 2007) and Radarsat 2 (spatial resolution 3m, launched by Canada in December 2007).

3.4. Future Missions

A serious of very high resolution optical satellites will be launched in near future like GeoEye-1, WorldView-2 having below 0.5m GSD. In addition Cartosat-3 is announced with 0.3m GSD and a proposal for GeoEye-2 with 0.25m GSD has been made.

ORFEO is planned to be launched in July 2008. ORFEO consists of an optical component – Pleiades (developed by France) and a radar one – Cosmo-Skymed (developed by Italy). The main advantages of Pleiades are represented by a very high spatial resolution (0,5m) and stereoscopic capabilities.

TanDEM-X will comprise of a second SAR satellite (TanDEM-X) flying in a tandem orbit configuration with TerraSAR-X. The main goal of TanDEM-X is to generate a high-precision (corresponding to the DTED-3 specifications), world-wide, consistent DEM.

4. Case Study

4.1 Introduction

Few months after the launch of SPOT 5, CNES (Centre National dÉtudes Spatiales) invited ISPRS (International Society for Photogrammetry and Remote Sensing) to join an initiative for assessing the new HRS (High Resolution Stereoscopic) instrument and the quality and accuracy of the DEM derived from the HRS stereo pairs.

In the frame of the HRS Scientific Assessment Program (HRS-SAP) nine test areas have been selected and analyzed. The selected sites were well diversified regarding the climate, relief and landscape in order to be representative of most situations in the world.

The article presents the scientific study (methodology, results and conclusions) made by the Institute of Photogrammetry and GeoInformation, Leibniz University Hannover, for test area Chiemsee.

4.2. Description of the Test Area Chiemsee

Test area Chiemsee is located in south-east of Germany in the federal state Bavaria, small parts of Austria are also included (figure 3). Two slightly overlapping SPOT 5 HRS - models are covering each an area of 120km x 60km.

The considered test area has mainly flat up to rolling relief and just a small part which includes the mountainous Alps. The height of the test area is ranging from 270m up to 1850 above the see level. This region is covered almost 20% by a mixture of smaller and larger forests and also some lake are included. The test area consists of 6 reference sub-areas: Prien, Gars, Peterskirchen, Taching, Inzell and Vilsbiburg (figure 4).

Fig. 3 Location of the test area Chiemsee (Bavaria, Germany)

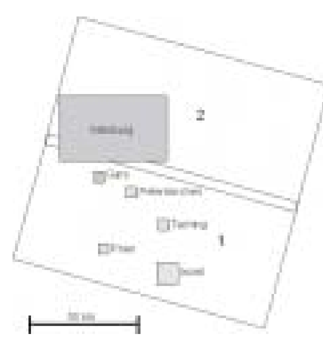


Fig. 4 Overlapping SPOT HRS-models and the reference areas

Test sub-area Prien (figure 5) has a size of 5km x 5km and its relief is flat up to rolling with heights ranging from 471m to 691m. Approximately 23% of the area is covered by forest (figure 6). The reference data (figure 7) is from airborne laser scanner and it is available with a point spacing of 5m.


Fig. 5 Topographic map of test area Prien


Fig. 6 Forest layer of test area Prien

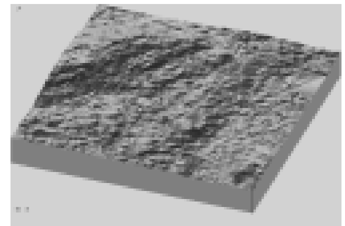


Fig. 7 3-D view of the reference DEM for Prien

Test sub-area Inzell (figure 8) is different from all the other test sub-areas. The size of the area is 10km x 10km. The region has a mountainous relief that includes steep parts of the Alps which are covered by forest. The heights are in the range from 610m up to 1681m.

The forest coverage is approximately 68% (figure 9). The reference DEM (figure 10) is in the moderate northern part (13%) from laser scanner with a vertical accuracy better than 0.5m and in the mountainous southern part (87%) from digitised contour lines from maps 1:10 000 with a vertical accuracy of only 5m. The point spacing is 25m both in X and in Y direction.


Fig. 8 Topographic map of test area Inzell

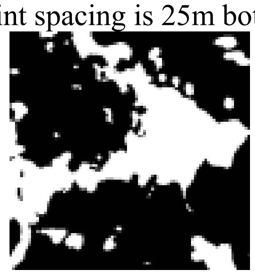


Fig. 9 Forest layer of test area Inzell

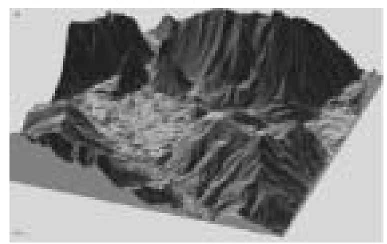


Fig. 10 3-D view of the reference DEM for Inzell

4.3. Methodology

In order to generate and analyze a digital elevation model for the test area Bavaria a sequence of programs was used. These programs are part of the Program System BLUH, created at the Institute of Photogrammetry and GeoInformation, Hannover, Germany.

Image orientation - the orientation of the SPOT HRS images was made using the program BLASPO. The control points used for the image orientation were usually located closely to road crossings in order to ease their identification. The image orientation was made using 46 control points in the southern model and 14 in the northern model (figure 11).


Fig. 11 Distribution of the control points in the southern stereo model (left) and the northern model (right)

The root mean square discrepancies at the control points after the image orientation are presented in Table 1. The results are similar for both models. The results of the image orientation are considered to be sufficient whereas the identification of the control points was made manually. The discrepancies in X and Y are influenced by problems of the point identification in the images. In the case of heights, the results are better and demonstrate that the HRS system has a higher accuracy potential. The vertical accuracy corresponds to a standard deviation of the x-parallax of 0.6 pixels.

Tabel 1: Discrepancies at the control points (southern and northern model)

Model	SX [m]	SY [m]	SZ [m]
Southern model	6.0	5.8	3.9
Northern model	7.7	5.0	3.5

Image matching **-** the image matching was made automatically using the program DPCOR. This program identifies corresponding image points in a model of two digital images without any information about the orientation. DPCOR is using a least squares matching method in the image space with region growing.

This method is based on the image contrast. In areas with sufficient contrast the matching leads to good results, but in areas without any contrast such as water surface or with limited grey value variations like forest areas the matching has problems or it is impossible to be done. The window size for automatic image matching was 10 pixels x 10 pixels.

In the southern model 85% to 90% of the possible points have been matched with a correlation coefficient exceeding 0.6 (figure 12). The plot of the matched points shows the distribution of matched points and the gaps in image matching. The root mean square y-parallax of the intersected rays has values between 4.67m and 7.11m with a mean value of 6.0m corresponding to 0.6 GSD for image component across the view direction. The result of the image matching is a file that contains corresponding pixel coordinates of the successfully matched points.

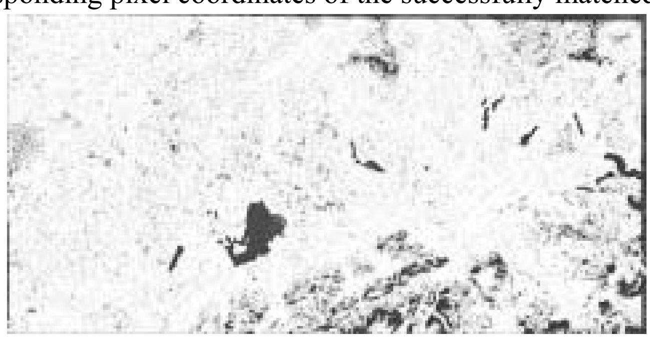


Fig. 12 Successful matched points (matched points - white) in southern scene

Using the program BLPRE the pixel coordinates are transformed to image coordinates. Then the rays belonging to these image coordinates are intersected by program COMSPO, leading to ground point coordinates. In total, approximately 27 million points have been determined in the southern model where the whole area of 12000 x 12000 pixels has been used and the northern model where only 12 000 x 8000 pixels where included.

Filtering **-** the program RASCOR can analyze, improve, smooth and interpolate a digital elevation model which may be created by automatic image matching, interferometric radar or laser scanning (LIDAR). RASCOR is eliminating the points which do not belong to the bare ground, generating a digital elevation model. In case of Prien, RASCOR removed 22.84% of the points in the first iteration and 53.39% in the second (figure 13), whereas for Inzell 23.32% points in the first iteration and 49.95% in the second (figure 14).

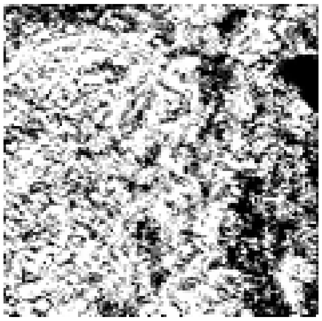


Fig. 13 Remaining points after filtering with RASCOR (white) 53.39% points removed for Prien

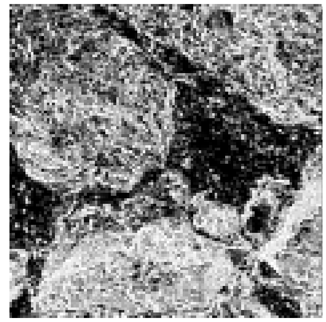


Fig. 14 Remaining points after filtering with RASCOR (white) 49.95% points removed for Inzell

DEMANAL is a program that evaluates the accuracy and accuracy characteristics of a DEM against a reference DEM. The analysis of a DEM is made separately for distinct land classes (for example forest), because the accuracy and the accuracy characteristics may be different from case to case. DEMANAL uses a geo-coded image layer for each land class.

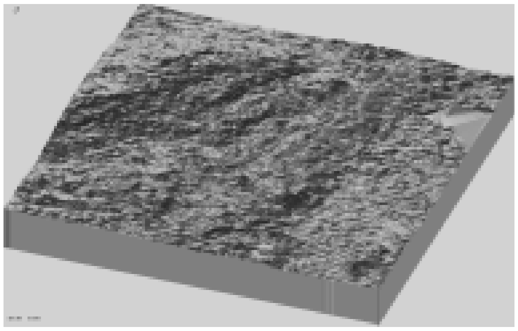
The program investigates in detail the discrepancies between the analyzed and a reference DEM and also as function of the terrain inclination and the height level. It is possible to define tolerance limits for the terrain inclination and the discrepancies of the DEM-points. The influence of a vertical scale difference can be respected iteratively.

4.4. Results

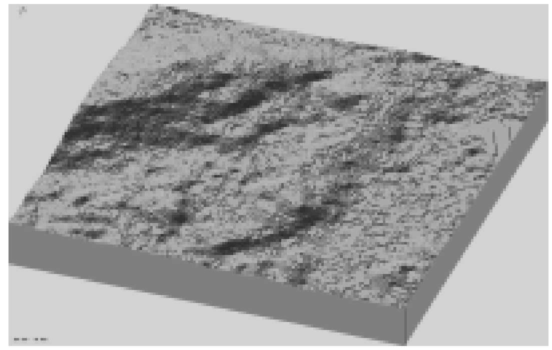
Prien - For the generation and analysis of the DEM of the area Prien, data from SPOT HRS and SRTM InSAR have been used (3D view - figure 15). The achieved results are shown in (table 2). The SPOT HRS DEM has a point spacing of 15m x 30m. The results achieved by means of INSAR SRTM are slightly better in both cases (open area and forest) than the results obtained using SPOT HRS images, but it has to be respected, that the SPOT HRS DEM contains more morphologic details because of the smaller point spacing.

Table 2: Results for test sub-area Prien (DSM, DEM-HRS, DEM-InSAR)
DSM = original matched points
DEM = filtered DSM

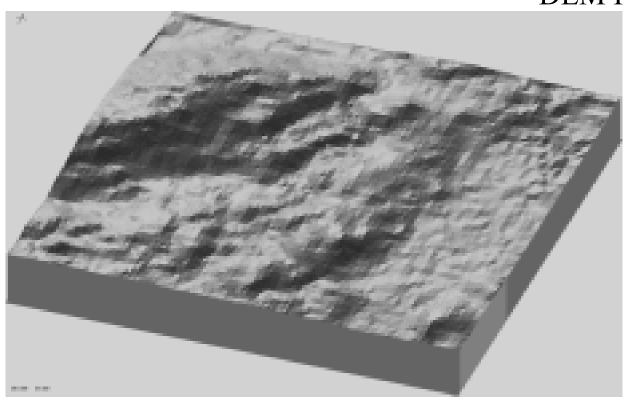
Digital Height Model	Test area	RMSZ	MEAN DZ	RMSZ without bias	SZ	Z*
DSM	all points	8.73	0.12	8.73	7.77 + 6.165 * tan α	-0.76 + 0.00195 * Z
	open area	6.03	-0.27	6.02	5.64 + 2.695 * tan α	-2.11 + 0.00351 * Z
	forest	10.37	0.08	10.37	9.83 + 1.731 * tan α	-3.74 + 0.00713 * Z
DEM (HRS)	all points	6.75	-0.70	6.72	5.74 + 7.144 * tan α	-4.54 + 0.00745 * Z
	open area	4.83	-1.01	4.72	4.58 + 1.990 * tan α	-1.09 + 0.00031 * Z
	forest	9.51	-0.99	9.46	8.53 + 4.625 * tan α	-3.20 + 0.00464 * Z
DEM (INSAR)	all points	6.77	1.05	6.69	6.22 + 3.892 * tan α	-0.64 + 0.00295 * Z
	open area	4.14	0.34	4.13	3.55 + 3.061 * tan α	-0.02 + 0.00063 * Z
	forest	6.96	0.61	6.94	6.93 – 1.217 * tan α	0.62 - 0.00084 * Z



DSM



DEM HRS



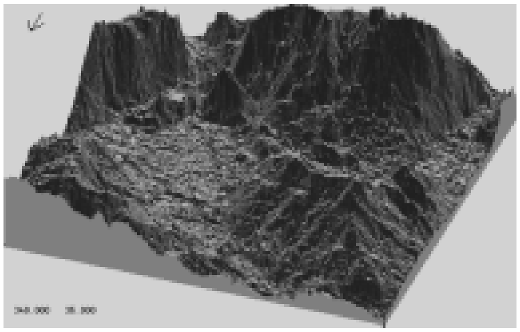
DEM INSAR

Fig. 15 Digital height models (Prien)
(exaggeration factor 1 time)

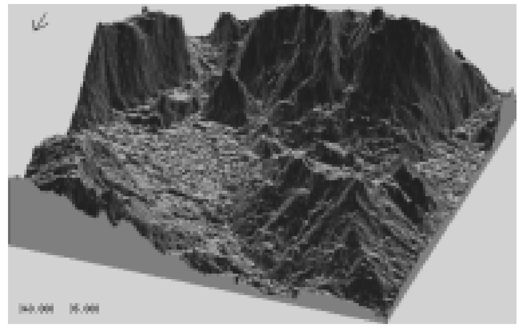
Inzell - like in the case of Prien for the generation and analysis of the DEM of the area Inzell, data from SPOT HRS and SRTM INSAR have been used. The results that have been achieved are shown in table 3. Inzell has a different character comparing to the other areas: the type of terrain is mountainous. The 3D view of the height models (DSM, DEM HRS, DEM INSAR) is presented below (figure 16).

Table 3: Results for test sub-area Inzell (DSM, DEM-HRS, DEM-InSAR)
DSM = original matched points
DEM = filtered DSM

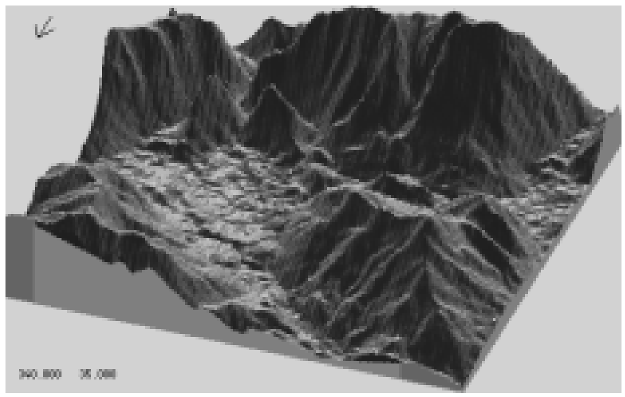
Digital Height Model	Test area	RMSZ	MEAN DZ	RMSZ without bias	SZ	Z*
DSM	all points	15.04	4.10	14.47	9.95 + 28.982 * tan α	1.79 + 0.00145 * Z
	open area	9.59	2.62	9.22	6.69 + 32.814 * tan α	-0.97 + 0.00510 * Z
	forest	14.45	1.03	14.41	9.82 + 17.133 * tan α	-1.28 + 0.00141 * Z
DEM (HRS)	all points	17.27	0.83	17.25	7.82 + 38.058 * tan α	0.63 - 0.00020 * Z
	open area	8.62	0.49	8.60	5.10 + 26.905 * tan α	0.15 + 0.00060 * Z
	forest	19.54	-0.91	19.52	8.91 + 34.634 * tan α	-1.68 + 0.00035 * Z
DEM (INSAR)	all points	10.52	2.54	10.21	8.12 + 4.294 * tan α	1.83 + 0.00012 * Z
	open area	8.02	2.45	7.64	5.66 + 10.531 * tan α	0.36 + 0.00296 * Z
	forest	9.34	0.25	9.34	5.45 + 6.013 * tan α	-0.54 + 0.00027 * Z



DSM



DEM HRS



DEM INSAR

Figure 16: Digital height models (Inzell)
(exaggeration factor 3 times)

5. Conclusions

For the investigated test area Chiemsee (Bavaria) in the frame of HRS SAP the filtering of the data was absolutely required because the C-band InSAR as well as the matched height models are representing the visual surface - that means the top of trees and buildings. In closed forest areas the effect of filtering is limited because not enough points of the bare ground are available. By this reason the accuracy of the DEM of areas covered by forests is below the accuracy achieved for open areas. A dependency of the accuracy from the terrain inclination is very clear.

The comparison between the accuracy of a DEM achieved by means of SPOT HRS images and the accuracy of a DEM obtained from INSAR SRTM for test areas Prien and Inzell showed that the results of the investigated points are better in the case of InSAR-SRTM; especially for forest areas the differences are significant and in open areas also better results were acquired but with small differences between them. SPOT HRS has some problems in matching forest areas because of the used spectral range from 0.48 up to 0.70μm wavelength, that means only the very first part of infrared is included, where the forest is always dark, leading to very narrow grey value distribution in forest areas. But the SRTM data do have the disadvantage of less detailed information caused by the spacing of 3 arc seconds (~90m) in comparison to 15m x 30m for SPOT HRS DEMs.

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