FFI RAPPORT

VALIDATION OF SRTM ELEVATION DATA IN NORWAY

WEYDAHL Dan Johan

FFI/RAPPORT-2005/02600

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FORSVARETS FORSKNINGSINSTITUTT
Norwegian Defence Research Establishment
P O Box 25, NO-2027 Kjeller, Norway

FORSVARETS FORSKNINGSINSTITUTT (FFI)
Norwegian Defence Research Establishment

P O BOX 25
N0-2027 KJELLER, NORWAY

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE
(when data entered)

REPORT DOCUMENTATION PAGE

1) PUBL/REPORT NUMBER FFI/RAPPORT-2005/02600 **1a) PROJECT REFERENCE** FFI-III/1002/170	**2) SECURITY CLASSIFICATION** UNCLASSIFIED **2a) DECLASSIFICATION/DOWNGRADING SCHEDULE** -	**3) NUMBER OF PAGES** 122

4) TITLE

VALIDATION OF SRTM ELEVATION DATA IN NORWAY

5) NAMES OF AUTHOR(S) IN FULL (surname first)

WEYDAHL Dan Johan

6) DISTRIBUTION STATEMENT

Approved for public release. Distribution unlimited. (Offentlig tilgjengelig)

7) INDEXING TERMS

	IN ENGLISH:	**IN NORWEGIAN:**
a)	Digital Elevation Model (DEM)	Digital høydemodell
b)	Remote Sensing	Fjernmåling
c)	Synthetic Aperture Radar (SAR)	Syntetisk aperture radar
d)	Shuttle	Romferge
e)	Vertical elevation accuracy	Vertikal høydenøyaktighet

THESAURUS REFERENCE:

8) ABSTRACT

The Shuttle Radar Topography Mission (SRTM) was carried out in February 2000. The goal was to produce a global and consistent digital elevation model with a grid posting of 30 m or 90 m, and with an absolute vertical accuracy better than 16 m (90 % confidence level).

FFI used data from the Vestfold and Bykle regions in Norway to validate the SRTM elevation data. Results show that the SRTM DEMs may have a small vertical offset from 0-3 meters. After correcting for vertical offsets in Vestfold, the SRTM X-band and C-band DEMs gave an absolute vertical accuracy of 5.2 m and 6.5 m (90 % confidence level) respectively for agricultural fields. This is much better than specifications. The SRTM interferometric SAR system will normally refer its elevations to the *reflective surface*. This causes dense Norwegian forest stands to introduce an SRTM elevation that is 15-17 m above the ground. This means that the SRTM system underestimates the true tree height by 6-8 m. On the contrary, the height of some large buildings is estimated within 1-2 m accuracy. It is also shown that hydroelectric power dams can be used to calibrate the SRTM DEMs to sub-meter accuracy. Poorer SRTM elevation accuracies are noted in areas of particularly low SAR backscatter (e.g. lakes or runways), or in terrain with steep slopes facing the SRTM radar beam direction.

The high quality SRTM DEMs can be recommended for many land mapping applications: substituting the 1:50 000 DEMs at many places, correcting/updating old maps, geocorrecting satellite images, or line-of-sight analysis.

9) DATE 2005-09-06	**AUTHORIZED BY** This page only Johnny Bardal	**POSITION** Director

ISBN 82-464-0974-3

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SECURITY CLASSIFICATION OF THIS PAGE
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1 INTRODUCTION

In the 1990's, there was an increased use of geographic information systems (GIS), satellite remote sensing and global modelling and monitoring systems. Many applications linked to these subjects would need a good digital elevation model. However, the best digital elevation model (DEM) that gave a global coverage was provided in a 1 km raster with varying quality. This DEM is available as the GLOBE, GTOPO30 and Digital Terrain Elevation Data (DTED) Level-0 products. Regionally, there exist quite good DEMs, but these are acquired with a variety of sensors and many different techniques are used during the elevation generation process.

A lot of research activities around the world have been focusing on the interferometric synthetic aperture radar (InSAR) technique after the launch of the European remote sensing satellites ERS-1 and ERS-2 in 1991 and 1995 respectively. Using the InSAR technique from space, it is possible to measure topographic heights or ground movements of the Earth surface. During the 1990's, the technique developed to the stage where it was possible to do InSAR processing for the production of DEMs on a large scale. Together with the two successful Shuttle SAR missions in 1994, this sped up the planning process for a global mapping mission using a pair of SAR antennas onboard the Shuttle.

The Shuttle Radar Topography Mission (SRTM) was carried out in February 2000. The SRTM mission was jointly performed by the National Aeronautics and Space Administration (NASA), the National Geospatial-Intelligence Agency (NGA), the German Aerospace Centre (DLR) and the Italian Space Agency [Rabus *et al.*, 2003]. The aim of this mission was to provide a near-global and consistent high-quality digital elevation model (DEM) at resolution levels of 3 and 1 arc sec. This will correspond to DTED Level 1 and 2 respectively [DTED Specification, 2000]. These two elevation data sets are often referred to as the "90 m" and "30 m" raster DEMs since their resolutions at equator equals approximately 30x30 m and 90x90 m.

The SRTM DEM is produced using the one-pass InSAR technique where a pair of SAR antennas will produce three-dimensional measurements of the Earth surface as it flies along [Zebker and Goldstein 1986, Gens and Van Genderen 1996]. In fact, the SRTM mission had two such radar antenna pairs operating simultaneously at C- and X-band radar frequencies. NASA with the Jet Propulsion Laboratory (JPL) was in charge of the C-band SAR, while DLR in Germany had responsibility for the X-band system.

The 11 days SRTM mission gave a global coverage between 60 degrees North and 56 degrees South for the C-band radar, while the X-SAR instrument gave gaps in its mapping pattern due to its limited swath width – only 45 km as compared to 225 km for the C-band ScanSAR system.

DLR made an Announcement of Opportunity (AO) in 1998. The Norwegian Defence Research Establishment (FFI) responded to this call through the proposal: “Analysis of SRTM data over vegetated and mountainous areas in south Norway”. This was accepted by DLR as SRTM AO-038 where the author is the principal investigator (PI). Several co-investigators are contributing to AO-038 by delivering background information or analysing the SRTM data. The co-investigators are: Norwegian Military Geographic Service (FMGT), Dept. of Mathematical Sciences and Technology at the Norwegian University of Life Sciences (former Agricultural University of Norway), and Centre for GIS & Earth Observation (before 2004: a remote sensing mapping division under Norwegian Mapping Authority).

SRTM AO-038 seeks to investigate the accuracy of the SRTM DEMs by means of two test sites in south Norway. The objectives of this project can be summarized as follows:

- Validate the SRTM DEM absolute height accuracy, which is specified to $\leq$ 16 m (with 90 % confidence) for both the C- and X-band DEMs. If this criterion is met, then the SRTM DEM is within the DTED Level-2 specifications (90% of points $\leq$ 18 m linear error), and the SRTM can then be used as the new global DTED-2 database [DTED Specification, 2000].
- Investigate height differences between the scattering centres of the X-band and C-band systems, particularly over forest areas.
- Understand what kind of topography and surface covers that will lead to unacceptable large errors in the SRTM DEMs
- Investigate any peculiarities found in the SRTM data sets.

A Master thesis was written in the spring 2003 by Jørn Sagstuen at Dept. of Mathematical Sciences and Technology at the Norwegian University of Life Sciences [Sagstuen, 2003]. He focused on the SRTM X-band DEM covering forest and open areas in Vestfold, Norway. Results show that the SRTM X-band DEM gives a lot of details not present in the 1:50 000 reference elevation data set that was used. These results were included in a presentation at the International Geoscience and Remote Sensing Symposium summer 2003 [Weydahl *et al.*, 2003]. More work on this SRTM AO was also presented at the European SAR Conference (EUSAR) in May 2004 [Weydahl, 2004].

The work presented in this report extends the SRTM analysis already presented in the above papers in three ways:

- It uses a higher-quality reference map in scale 1:5000, instead of 1:50 000, over one of the Norwegian test sites.
- It extends the comparison of the C-band and X-band SRTM DEMs.
- It studies several man-made objects in detail.

This report first gives some background with respect to SAR interferometry and the SRTM mission. The two Norwegian test sites are presented and details of the various data sets given. The criteria for the accuracy requirements are explained before the different pre-processing steps are shown. Many interesting results from the two Norwegian test sites are then given. Finally, the report draws some conclusions and gives recommendations with respect to using the SRTM DEM for various applications.

2 BACKGROUND

2.1 SAR interferometry

Since the launch of the ERS-1 satellite by the European Space Agency (ESA) in 1991, the topic of interferometric processing of signals from Synthetic Aperture Radar (SAR) systems has gained a lot of attention in the radar remote sensing community [Allen 1995, Gens and Van Genderen 1996, Massonnet and Feigl 1998, Rosen *et al.* 2000].

The interferometric SAR (InSAR) technique allows the creation of digital elevation maps [Zebker and Goldstein 1986], but also deformation measurements [Massonnet *et al.* 1993]. These SAR measurements can be performed regardless of cloud cover and light conditions. By using spaceborne SAR platforms, it is possible to acquire data from most of the Earth's surface within a limited time period only restricted by the satellite orbit repetition pattern.

The SAR sensor not only records the power of the backscattered electromagnetic radiation, but also its phase. The observed phase is a summation of the phases of all the scattering elements located within a resolution element. The absolute phases of pixels in a SAR image are actually quite random, and a phase plot of only one SAR image would not contain any useful information. If, however, the summation of all these scattering elements is the same for a second image, then the signals are *coherent*. This means that the differences between the phases in the first and second image will vary only due to path length differences.

InSAR makes use of two different SAR images taken over the same target terrain from almost identical perspectives. See the illustration in Figure 2.1. The spatial separation of the two SAR antenna positions (also frequently called *spatial baseline*, *B*) can typically be in the order of a few decimetres to several hundred metres.

For a *repeat-pass* InSAR system, the two SAR images are taken at different times (e.g. several days or months apart) by the same sensor. Examples of repeat-pass satellite systems are: ERS-1, ERS-2, RADARSAT-1, ENVISAT. A *single-pass* InSAR system, on the other hand, will normally have two antennas where one is the transmit/receive master antenna and the other is a receive-only slave antenna (e.g. airborne systems and the SRTM).

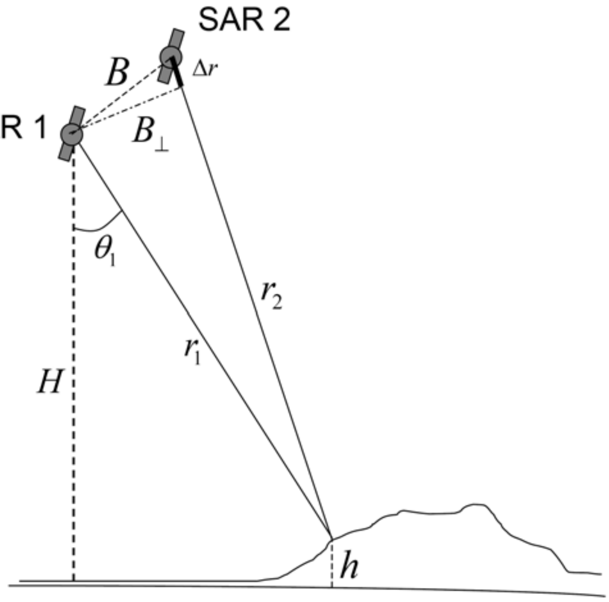


Figure 2.1 *Interferometric SAR geometry for a repeat-pass satellite system with radar look angle* θ_1 *for the first satellite pass. The interferometric phase will correspond to the difference in distance (i.e.* $\Delta r = r_2 - r_1$*) from the two antenna positions to a position on the Earth surface.*

In either case, the two SAR images are first coregistered before their phase differences are combined into an *interferogram*. The *phase difference* for each pixel of the interferogram is a measure of the change in distances between the scatterer and the SAR antenna (denoted r_1 and r_2 in Figure 2.1) for the two SAR images at hand. The phase difference ϕ of two corresponding pixels observed within the two SAR images is thus related to the range difference via:

$$\phi = p\frac{2\pi}{\lambda}\left(r_2 - r_1\right) \qquad (2.1)$$

where $p = 2$ for repeat-pass or $p = 1$ for single-pass interferometry, and λ is the radar frequency. The phase difference ϕ is measured modulo 2π, which results in a characteristic *fringe* pattern often seen in the SAR interferograms (e.g. see middle image in Figure 2.2). This interference pattern will contain all the information on relative geometry. Thus, an interferogram can represent elevation heights and/or geophysical motions of the terrain (e.g. displacements after earthquakes, or subsidence). A proper estimate of the terrain height and/or ground motion can only be obtained after first removing the 2π phase ambiguity in the interferogram through a procedure called *phase unwrapping* [Gens and Van Genderen 1996].

Now, if no large-scale deformations occur between the recordings, then the distances r_1 and r_2 can be used together with the phase difference to solve geometrically for the height of the target, *h*. These terrain heights may need further corrections or calibration. This can be performed by a set of known elevation control points within the SAR scene. Finally, it is then possible to derive a DEM with *absolute* terrain heights.

Figure 2.2 shows an SRTM SAR amplitude image (one out of two) together with the corresponding interferogram and the derived DEM. Note the characteristic fringe pattern (2π phase change) seen in the interferogram.

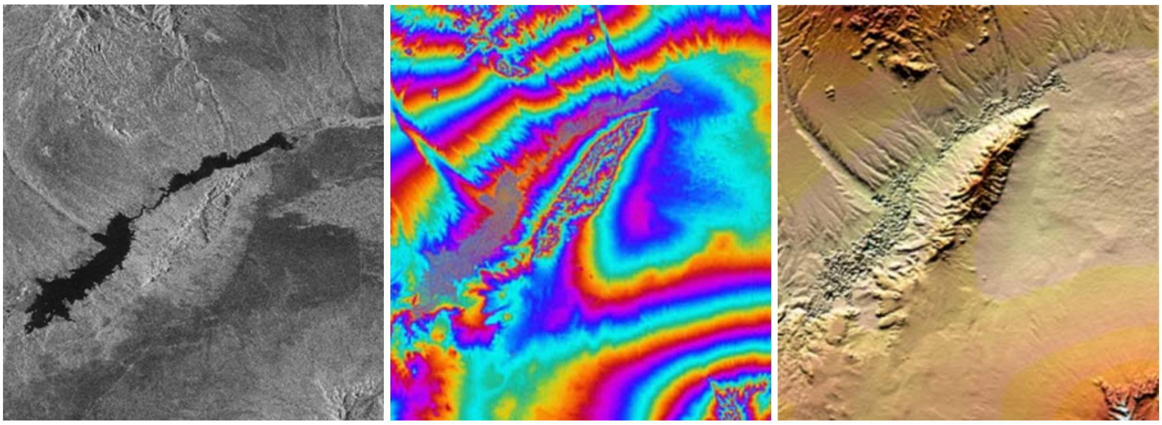


Figure 2.2 Interferometric processing showing one out of two SAR images (left), the corresponding interferogram (middle), and extracted DEM (right). Data acquired by the SRTM C-band SAR instrument over California. © JPL 2000.

2.2 InSAR height sensitivity

Now, the height-to-phase sensitivity of a SAR interferometer can be written [Rabus et al. 2003]:

$$\frac{\delta\phi}{\delta h} = \frac{p 2\pi B_\perp}{\lambda r_1 \sin\theta_1} \qquad (2.2)$$

where $B_\perp$ is the spatial baseline component perpendicular to the radar look direction θ_1 is the radar beam look angle of the first SAR antenna, and p is 1 for single-pass or 2 for repeat-pass configurations. r_1 is the radar distance to the target for the first antenna. Substituting 2π for $\delta\phi$ will give us the elevation difference between adjacent fringes in an interferogram, also called the *altitude of ambiguity*.

From equation (2.2) we can see that in order to get a better height sensitivity, one would desire to operate at large spatial baselines or shorter λ. From the interferogram point of view, this would give a denser fringe pattern. Larger spatial baselines, however, lead to larger differences in look angles. This will cause spatial decorrelation of the InSAR phase since the relative positions of the radar scatterers within a pixel changes [Gatelli et al. 1994]. When this change becomes greater than the radar wavelength, the phase coherence is zero and we can no longer perform a pixel-by-pixel phase comparison between the first and second SAR image [Li and Goldstein 1990, Zebker and Villasenor 1992]. At this stage, an upper limit is reached for the interferometric spatial baseline. This is often called the *critical baseline*, and can typically be in the order of a few hundred metres to a few kilometres. For the ERS-1 and ERS-2 SAR systems, the critical baseline will be approximately 1.1 km. Thus, a baseline between 100 m and 600 m may prove to be optimal when using ERS SAR images for topographic mapping.

The SRTM mission was first planned with a spatial baseline, B, of 30 m. This was changed to 60 m during the planning process since a longer spatial baseline would give better height-to-phase sensitivity, and thus higher elevation accuracies. The ambiguity of elevation for the 60 m SRTM baseline is approximately 175 m and 316 m for the X- and C-band SAR systems respectively [Rabus et al. 2003]. This would have been doubled if the antenna baseline had been only 30 m.

We have seen that the phase coherence will decrease linearly with increasing spatial baseline. There are also other factors that will contribute to the overall decorrelation of the InSAR signal. These are discussed in the next section.

2.3 Sources of InSAR height errors

Reduced InSAR coherence is directly related to errors in the InSAR phase. This will in turn cause errors in the interferometric height estimate. The InSAR phase errors can roughly be divided into three groups:

1) InSAR parameters during data acquisition. (E.g. errors in the antenna spatial baseline estimation and errors when estimating the orbital trajectories.)

2) InSAR processing steps after acquiring the raw data. (E.g. SAR processing inaccuracies, low S/N ratio in the SAR image, SAR image co-registration inaccuracies.)

3) Influences caused by vegetation, land cover changes, meteorological factors (precipitation, freezing and thawing), and atmospheric conditions.

The state-of-the-art SAR processors of today will normally be able to preserve the phase in an optimal manner. They will also be able to co-register the InSAR image pair to accuracies better than 1/10 of a pixel. The InSAR processing steps will therefore normally not introduce any significant phase errors.

Generally speaking, atmospheric inhomogeneities may cause spatially varying wave propagation delays. Typical spatial scales are in the km regime. For single-pass InSAR with a short baseline, these signals will cancel out since the two antennas will “look” through the same atmospheric condition [Bamler 1999]. Repeat-pass InSAR may, on the other hand, experiences phase errors in the order of a fraction of a phase cycle. This phase error effect can be reduced by optimum averaging of several repeat-pass interferograms [Ferretti et al. 1997].

After eliminating several factors, we are left with the following major phase error sources:

a) Any error in the *attitude* (roll) of the spatial baseline will give a tilt of the DEM by the same angle.

b) An error in the spatial baseline length will lead to an over/under estimation of the terrain height, and to a small non-linear distortion of the DEM. The phase error sources in a) and b) are of large scale and can be reduced by introducing a set of ground control points.

c) Error in spatial baseline position. This translates directly to a height error in the same order of magnitude.

d) Phase measurement noise translates into random height errors of short correlation length. Equation (2.2) can then be written as [Zebker and Villasenor 1992, Bamler 1999]:

$$\delta h = \frac{\lambda r_1 \sin\theta_1}{p 2\pi B_\perp}\delta\phi \qquad (2.3)$$

With a single-pass InSAR system (e.g. SRTM), phase noise is caused by thermal and quantization noise of the radar receivers.

Repeat-pass systems (e.g. ERS and ENVISAT) will suffer from temporal decorrelation of the imaged scatterers [Rignot and van Zyl 1993, Wegmüller and Werner 1997, Weydahl 2001a, Weydahl 2001b]. The result is larger DEM inaccuracies over forest areas and in areas of changing surface conditions (e.g. precipitation, seasonal changes). Also, the signal will completely decorrelate over water bodies. For these reasons, one will prefer to use a single-pass InSAR system when generating high-precision DEMs. This is achieved with the SRTM mission.

High frequency noise-induced errors determine what is often referred to as relative accuracy, while absolute accuracy also includes large-scale (attitude induced) errors [Bamler 1999].

2.4 The SRTM mission

The SRTM mission was set up to generate a near-global digital elevation model of the Earth using radar interferometry. The result was intended to be the most accurate, consistent, and globally available DEM of the Earth land surface ever made. SRTM was a joint mission of NASA and DLR, in partnership with NGA and the Italian Space Agency.

The SRTM instrument consisted of the Spaceborne Imaging Radar-C (SIR-C) hardware set as well as the spaceborne X-band SAR system. JPL had the responsibility for the C-band SAR system, and DLR for the X-band SAR. Both SAR systems had been flown on the Shuttle, in 1994, but now these two systems were modified with a Space Station-derived mast and additional antennas to form an interferometer with a 60 m long spatial baseline. See illustration in Figure 2.3.

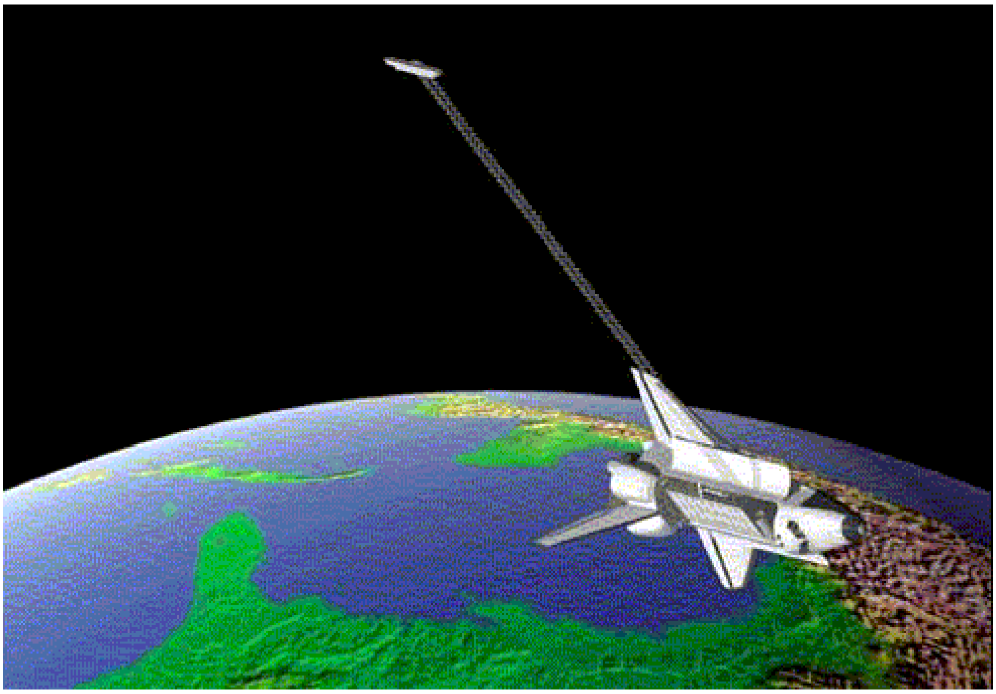


Figure 2.3 An artistic illustration of the Shuttle "Endeavour" with the 60 m long radar antenna mast deployed, ready for collecting SAR data during the 11 days SRTM mission in February 2000.

The SRTM mission was delayed several times in 1999, but the launch of the Shuttle Endeavour finally succeeded on the 11th February 2000. During its 11 days mission, Endeavour operated at an altitude of 233 km with an inclination of 57°. The C-band ScanSAR system covered a 225 km wide strip on the Earth surface, while the X-band StripMap SAR system only covered a swath width of 45 km.

An illustration of the SRTM flight configuration and beam geometry is shown in Figure 2.4. One may notice that the X-band system uses vertical polarisation, while the C-band ScanSAR sub-swaths have different polarisations.

The system specifications led to a global coverage between 60° North and 56° South for the C-band SAR system, see Figure 2.5. Thus, 80 % of the Earth land mass was mapped. On the contrary, the X-band SAR instrument gave gaps in its mapping pattern due to its limited swath width, see Figure 2.6. However, an advantage with the shorter wavelength X-band system is that it will give better relative height accuracies by almost a factor of 2 as compared to the C-band system [Rabus et al. 2003].

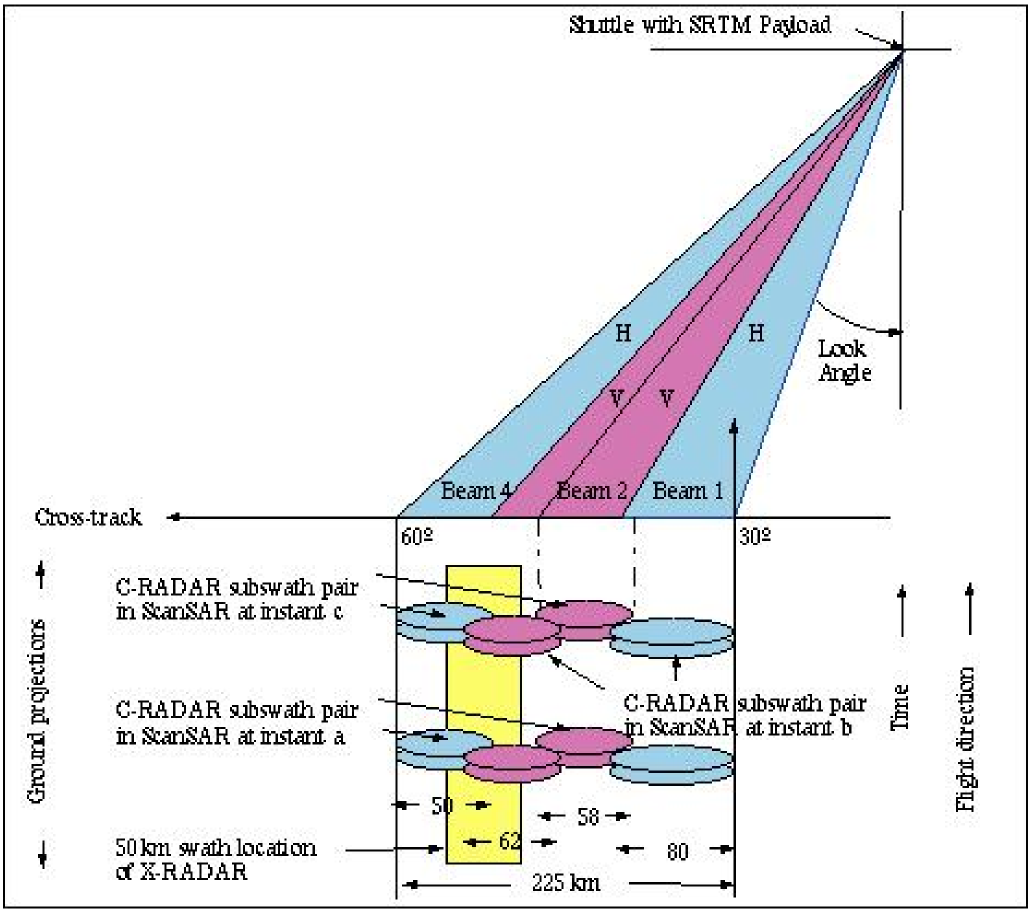


Figure 2.4 SRTM flight configuration and beam geometry. (Illustration from DLR.)

The C-band SAR system covered 95 % of the available land surface at least twice, 50 % at least three times, and 24 % at least four times. Although the X-band SAR system does not give a global coverage like the C-band SAR system, the acquired swaths will overlap more and more as the Shuttle approaches the turning points in the North and South. The SRTM X-band SAR was therefore able to give a total coverage over the Norwegian territory up to 60º15' North, see Figure 2.6 and Figure 7.2.

The C-band SAR instrument was operated at all times the Shuttle was over land and about 1000 individual swaths were acquired over the ten days of mapping operations. This gave 8.6 Terabyte of C-band SAR raw data. Adding up the X-band SAR data, a total of 12.2 Terabyte of raw data was collected on 332 digital tapes during the 11 days SRTM mission.

JPL in the US had the responsibility for processing the global C-band SAR raw data set, while DLR in Germany processed the X-band SAR data. The Italian Space Agency processed the data over Italy. The main goal was to process the SAR data to digital elevation models, although different SAR image products also can be delivered.

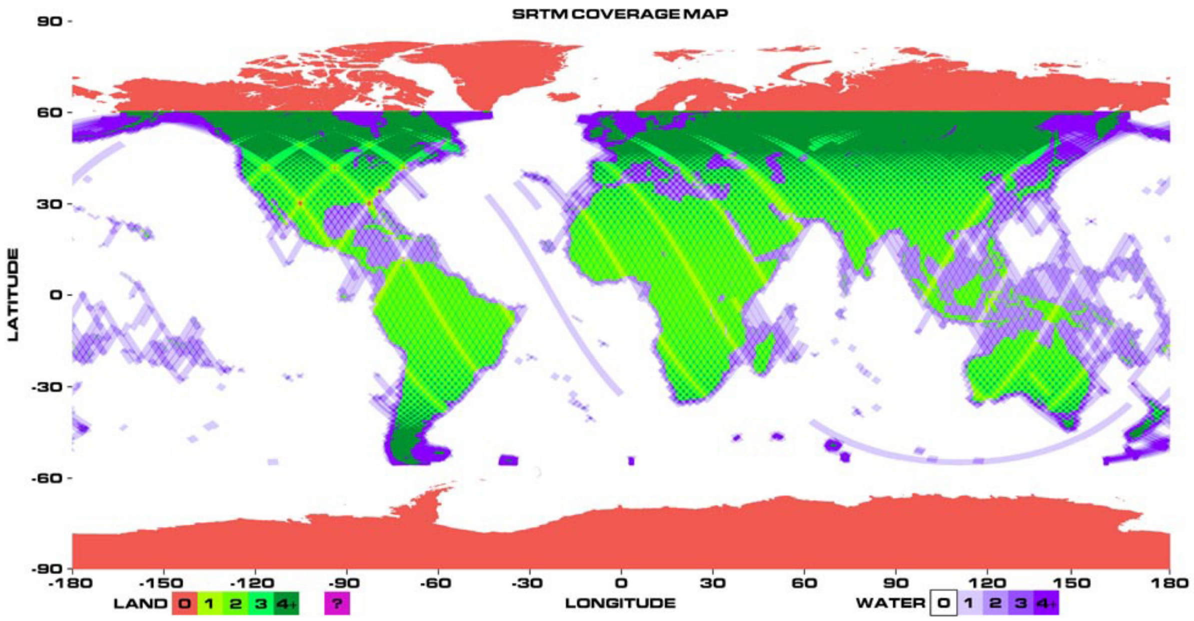


Figure 2.5 *The global SRTM C-band SAR coverage. The colours indicate how many times the SAR instrument was able to cover a given geographic region. 95 % of the land areas between –56 South and +60 North are in fact covered at least twice. 24 % of the same areas are covered at least four times. [From JPL web page.]*

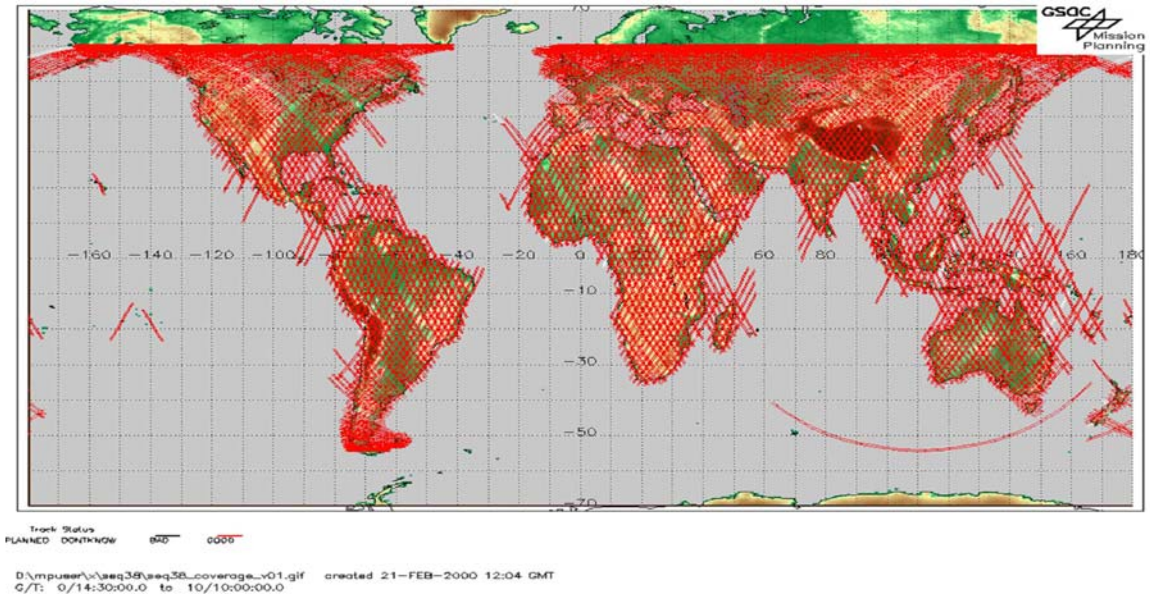


Figure 2.6 *The SRTM X-band SAR coverage is shown as red strips in the map. It is evident that the 45 km wide swath led to large gaps in the global mapping, and that the overall coverage was better at the higher/lower latitudes. [From DLR web page.]*

The SRTM SAR instrument system consists of four main parts [SRTM main web page at JPL, 2005]:

- The main antenna system.
- The mast structure.
- The outboard antenna.
- The Attitude and Orbit Determination Avionics (AODA).

The main antenna system is located inside the bay of the Shuttle. It can transmit C-band and X-band radar signals towards the Earth surface. The returned echo is received by the main antenna as well as the outboard antenna located at the tip of the 60 m long mast.

The length of the mast was first planned to be 30 m. However, a longer antenna baseline would give higher DEM accuracies (see section 2.1 and equation (2.2)). So, when a company in California came up with a solution for a 60 m long mast structure, this was selected.

The SRTM mast is the Able Deployable Articulated Mast (ADAM) with a truss structure that consists of 87 cube-shaped sections, called bays. Unique latches on the diagonal members of the truss allow the mechanism to deploy bay-by-bay out of the mast canister, see Figure 2.7. The canister housed the mast during launch and landing, and it also deployed and retracted the mast using a motor driven nut within the mast canister. The mast could also be deployed manually using a hand-held motor [SRTM main web page at JPL, 2005].

The 60 m long mast in the SRTM system will make it a fixed temporal baseline, one-pass (rather than a repeat-pass) SAR interferometer. This gives hardly any temporal decorrelation of the interferometric signal (as compared to the repeat-pass ERS SAR, RADARSAT-1 or ENVISAT ASAR systems). Thus, quite accurate measurements should be feasible after correcting for the systematic error sources.

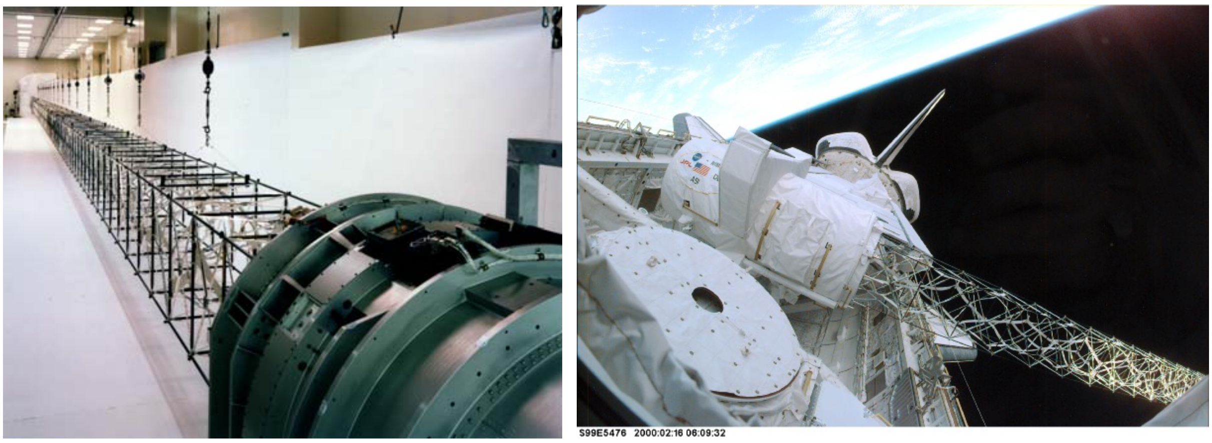


Figure 2.7 The SRTM mast fully extended, looking from the canister end (left). Photo taken during the mission (right). [From JPL web page of the SRTM instruments.]

The most important systematic errors are caused by inaccuracies in the SAR antenna positions and pointing direction. The absolute position of the baseline in space was measured by two GPS receivers located on the outboard radar antenna structure with an accuracy of about 1 m. This small error contributes directly to the DEM height error.

Much more critical was the baseline length and angle in space. A 0.3 mm bending of the tip of the 60 m mast would lead to a height error of 1.5 m on the ground when exploiting the X-band SAR data. Similarly, a dynamic baseline length variation of 1 mm would lead to about 0.5 m DEM error [Rabus et al. 2003]. Therefore, one of the key components of the interferometer is the Attitude and Orbit Determination Avionics (AODA), comprising of a suite of instruments to measure the Shuttle position and attitude, and the boom tip location relative to the Shuttle. Attitude information was derived from a combination of star tracker and inertial reference unit (IRU) measurements. The boom tip location was determined with an optical target tracker, which measures the angles to several targets located on the tip structure, and an electronic ranging device used to measure the distance to the boom tip [Rosen et al. 2001]. The accuracy of the combined AODA subsystems was specified to give a 10 m DEM height error over the 11-day mission, or 2.8 m height error within 30 seconds of SRTM SAR acquisitions [Rabus et al. 2003].

Now, the thrusters on the outboard antenna did not work properly during the SRTM mission. This gave extra problems when calibrating and correcting for the SRTM antenna motions prior to the interferometric DEM processing. However, after a long calibration period at DLR and JPL from the year 2000 to 2002, the first SRTM X-band DEMs were delivered to AO-038 (i.e. the project described in this report) in late 2002.

We have seen that errors in the baseline orientation cause errors in absolute elevation, e.g., with respect to the centre of mass of the Earth, but the relative heights within the radar swath are largely unaffected. This means that a few ground control points can be used to calibrate absolute height estimates even in the absence of accurate attitude information. The ocean surface (zero elevation), as well as some selected corner reflector positions, is therefore used by the JPL and DLR processing facilities to calibrate the final SRTM DEMs.

2.5 SAR backscatter and penetration

The *strength* of the backscattered SAR signal will be influenced by factors like: radar wavelength, radar look angle, polarisation, surface roughness, surface moisture content, vegetation density and type. A strong SAR backscatter means a high signal-to-noise ratio. The estimated interferometric elevation height will in such areas be more accurate than in low-backscatter areas (e.g. areas with smooth bare ground, water surfaces with calm wind conditions, and runways). This will be discussed in more detail in chapter 7.1.

The most important factors governing the SAR signal *penetration depth* in bare ground, vegetation canopy and snow covered regions will be moisture content and radar wavelength. Generally speaking, the SAR signal will penetrate deeper in dry conditions and at longer wavelengths. This is illustrated in Figure 2.8. A practical implication for the SRTM system is that:

- The C-band and X-band systems will only partly penetrate the canopy in dense forest stands.
- The C-band system may penetrate slightly deeper into the vegetation than the X-band system.

As a consequence, the SRTM elevations are defined with respect to the *reflective surface* computed from the InSAR returns from the Earth features [DTED Specification 2000]. The SRTM DEMs will therefore include cultural features (man-made) and vegetation canopy elevations. Several examples of this are shown in chapter 7.7. An SRTM DEM may therefore correctly be referred to as a *digital surface map* (DSM) rather than a digital terrain map (DTM).

The SRTM C-band SAR system uses a ScanSAR configuration with four sub-swaths. The outer swaths use horizontal polarisation on transmit and receive (HH), while the two inner swaths use vertical polarisation (VV). HH and VV may have slightly different penetration depths in a forest or vegetation structure. However, for the SRTM system it is assumed that this penetration difference (and thus different reflective surface heights) is much smaller than the specified vertical accuracy (< 16 m at 90 % confidence). Small vertical inaccuracies caused by different polarisations will therefore be more of an academic interest (rather than practical).

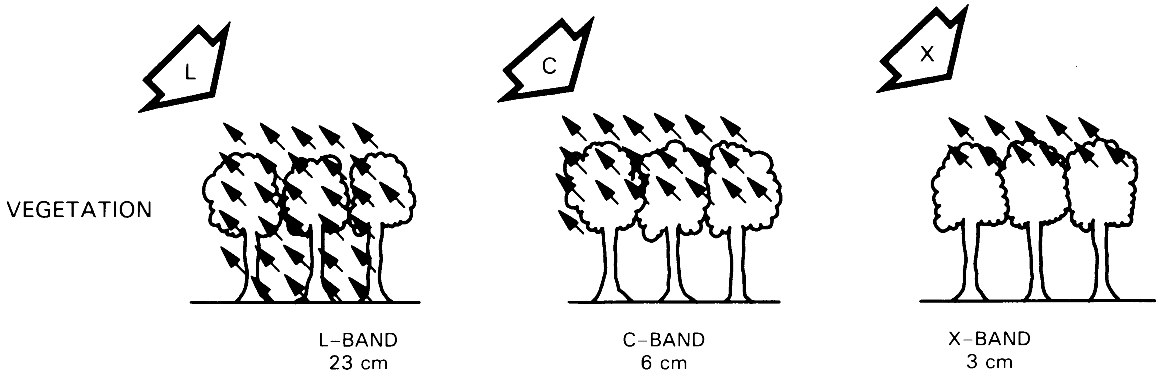


Figure 2.8 Penetration capability of a multi-frequency radar system through vegetation. [From NASA Instrument Panel Report, 1989.]

2.6 SRTM DEM product specifications

The SRTM mission was designed to produce a global and consistent DTED-2 dataset based on the interferometric SAR technique. A set of product specifications was set up before the SRTM mission. Parts of the SRTM product specifications are clearly governed by the DTED-2 format (spatial resolution, pixel size, datum, data format), see Table 2.1. The horizontal and vertical accuracies are specified according to theoretical achievements expected for the SRTM system. It is expected that the relative vertical accuracy will be better for the shorter wavelength X-band system, see Table 2.1. Note that it is the products from the two coloured coloumns that are evaluated in this report.

	SRTM X-band DEM	**SRTM C-band DEM**	**SRTM C-band DEM**
Product availability	public	public	restricted
Spatial resolution	30 m x 30 m	90 m x 90 m	30 m x 30 m
Pixel size	1x1 arc sec	3x3 arc sec	1x1 arc sec
Datum (horizontal)	WGS84	WGS84	WGS84
Datum (vertical)	WGS84 ellipsoid / geoid	geoid	geoid
Elevation intervals	1 m	1 m	1 m
Data format	16-bit signed integer	16-bit signed integer	16-bit signed integer
Absolute horizontal accuracy (90 % circular error)	± 20 m	± 60 m	± 20 m
Relative horizontal accuracy (90 % circular error)	± 15 m	± 45 m	± 15 m
Absolute vertical accuracy (90 % linear error)	± 16 m	± 16 m	± 16 m
Relative vertical accuracy (90 % linear error)	± 6 m	± 10 m	± 10 m

Table 2.1 Product specifications of the SRTM X-band DEM and C-band DEM. The two coloured products are the ones evaluated in this report.

3 TEST SITES

The SRTM AO-038 project is using two test sites in the southern part of Norway. Both test sites are located south of 60 degrees North. The test sites are marked in Figure 3.1, and are described in more detail in the next sections.

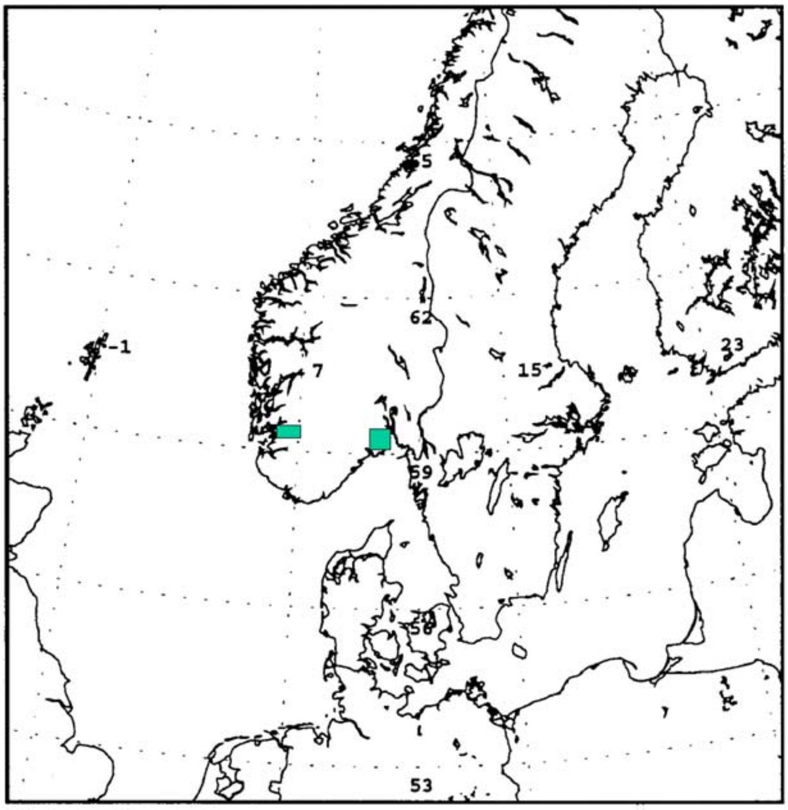


Figure 3.1 Map showing the southern part of Norway with the two test sites: Bykle (left) and Vestfold (right).

3.1 Vestfold

The first SRTM test site is approximately 33 km x 37 km in size, and covers large parts of the Vestfold County. Vestfold is located southwest of Oslo at the western part of Oslofjorden in Norway. The test area is marked inside the optical multispectral satellite image in Figure 3.2. Agricultural land, forested areas, many lakes and three cities (Horten, Tønsberg and Sandefjord) are typical surface cover types dominating this area. The elevations span from sea level at Oslofjorden in the East, to mountains reaching up to 420 m in the West.

The Vestfold test area is characterized by rolling topography with very few cliffs and steep slopes. Coniferous or deciduous trees cover most hillsides.

There are several reasons why the Vestfold area was chosen as one of the two test sites:

- It is easily accessible for field observations and deploying radar corner reflectors.
- Many digital reference data sets exist (both digital maps and remote sensing images).
- A high quality digital topographic map (N5) covers most of the area.
- It holds a variety of surface cover classes, including agricultural fields and forest.
- There are many places of dense coniferous and deciduous forest. It should then be possible to investigate to what degree dense forest stands will model the X- and C-band SRTM DEMs.
- The area spans an interesting topographic range from sea level and up to 420 meters.
- There are very few places of extreme relief that may distort the SAR viewing capability (i.e. shadow or layover effects).

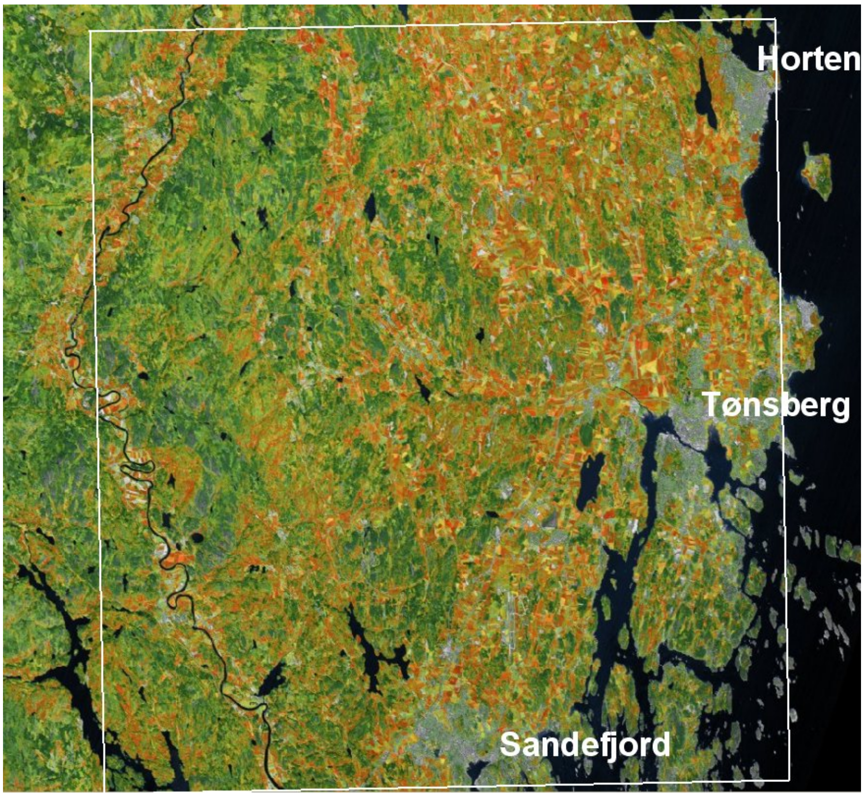


Figure 3.2 The test area in Vestfold marked on an optical multispectral IRS-1C satellite image from summer 1997. The satellite image is given in the WGS84 UTM projection. (IRS-1C image: © Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997.)

3.2 Bykle

The Bykle test area is located in the southwestern part of Norway and has an extent of approximately 43 km x 28 km. Fjords and steep valleys cut through the landscape that spans from sea level to 1486 m above sea level. There are numerous small lakes in the mountains, as well as several hydroelectric dams. Most of these lake surfaces were covered by ice during the SRTM acquisition in February 2000.

Small bushes, heather and rock form the dominant ground surface cover above 900 meters. This is also indicated in the 1:250 000 map from Norwegian Mapping Authority seen in Figure 3.3.

There are several reasons for using the Bykle region as the second test site:

- It spans a wide range of elevation heights from sea level to 1480 m.
- There is hardly any forest above 900 meters, so the SRTM DEM accuracy can be evaluated without thinking of forest stands that may model the SRTM terrain heights.
- There are many examples of extreme sloping terrain in the region that really will put the SRTM DEMs to the test (i.e. SAR layover and shadow effects will lead to no valid DEM data).
- There are several hydroelectric dams in the region. These can be used as height reference levels since The Norwegian Water Resources and Energy Directorate (NVE) measure them to centimetre accuracy.
- A digital reference map (N50) exists, produced from 1:50 000 topographic maps.

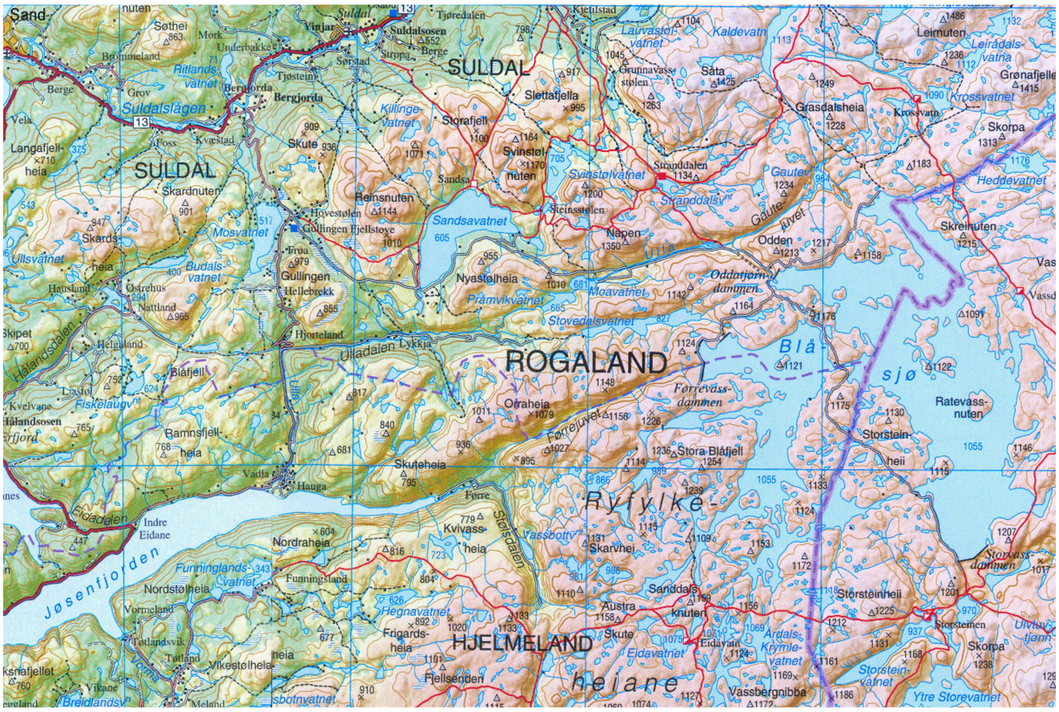


Figure 3.3 Map over the 1180 km^2 (42.6 km x 27.7 km) large test area near Bykle in south Norway. © Statens Kartverk/Kunnskapsforlaget Det Store Norgesatlas 2003.

4 DATA SETS

There are several data sources used in this study. Short descriptions of the different data sets are shortly given underneath.

4.1 SRTM X-band DEM

DLR in Germany processed the SRTM X-band SAR data. FFI received the first batch of SRTM X-band data in December 2002.

The SRTM X-band DEM is given in the DTED format. The sample spacing for individual data points is 3 arc-seconds. The projection is geographic (Lat/Lon), and the spheroid is WGS84. One DEM raster file has a size of 901 x 901 samples (16-bit signed integer) and covers one quarter of a full latitude/longitude tile, see also [SRTM main web page at DLR, 2005].

4.2 SRTM X-band HEM

DLR provides a Height Error Map (HEM) along with the SRTM X-band DEM. The HEM shows assumed height error (given in meters) for each pixel. These errors are theoretical estimates of how accurate a pixel in the X-band DEM is. The HEM is thus derived from the interferometric coherence, phase unwrapping errors, and the mapping geometry. The HEM is given in the DTED format. The projection is geographic (Lat/Lon), and the spheroid is WGS84.

4.3 SRTM X-band SAR images

There are several SRTM X-band SAR images from the test areas. Both the geocoded terrain-corrected (GTC) image and the geocoded incidence angle mask (GIM) have a spatial resolution and pixel spacing of 25 m. The pixels are represented in 16-bit signed integer. These products use the UTM projection, and the spheroid is WGS84. The GTC image shows the SAR amplitude in dB. The data representation in the GIM image is organized so that: bit 0 = layover, bit 1 = shadow, bit 2 to 6 = incidence angle.

4.4 SRTM C-band DEM

JPL in USA processed the SRTM C-band data on their supercomputer system, and delivered the resulting DEMs to U.S. Geological Survey (USGS).

The SRTM data are organized into individual rasterized cells, or tiles, each covering one degree by one degree in latitude and longitude. Sample spacing for individual data points is either 1 arc-second or 3 arc-seconds. Since 1 arc-second at the equator corresponds to roughly 30 meters in horizontal direction, the sets are sometimes referred to as “30 m” or “90 m” data. For the latitudes of our test sites in southern Norway (59.3 degrees North), this corresponds to approximately 93 m x 47 m in the northing and easting directions for the 3 arc-second data, see also Table 4.1.

The C-band DEM can be delivered as *unedited* or *finished* data [SRTM web page at JPL showing data products 2005, SRTM web page showing overview of data products at USGS 2005]. The *unedited* data hold fairly raw elevation data obtained from the JPL InSAR processing. These DEMs contain numerous *voids* and spurious points such as anomalously high (spike) or low (well) values. Water bodies will generally not be well defined. Rather, they will appear quite noisy or rough in the elevation data since these surfaces generally produce very low SAR backscatter. The 3 arc-second (“90 m”) *unedited* data are generated by 3x3 averaging of the 1 arc-second (“30 m”) data. This means that 9 samples are combined in each 3 arc-second data point. Now, since the primary error source in the SRTM elevation data has the characteristic of random noise (SAR speckle), this averaging process reduces the error by roughly a factor of three! These *unedited* data are better suited for research than the *finished* data.

The *finished* data has been through an editing process. *Void* areas are filled, the water boundaries are better defined based on auxiliary data, smaller islands are removed according to the DTED standards, and lakes have been given a fixed elevation value. The “90 m” *finished* data are produced by picking every third pixel in the “30 m” data set. A plain averaging is therefore not performed. The *finished* C-band data products (both “30 m” and “90 m”) are distributed through the United States Geological Survey’s (USGS) EROS Data Center, and can be ordered or downloaded through Internet [SRTM web page for download of seamless USGS data 2005, SRTM web page with download of *finished* C-band data 2005].

SRTM product	**Northing**	**Easting**
X-band DEM from DLR in Germany:		
Pixels in file	901	901
Pixel size (degrees)	0.0002777	0.0002777
Estimated pixel size (m) at 59.30 degrees North (i.e. the Norwegian test sites)	30.9	15.8
Unedited C-band DEM from the “free” ftp-site in USA:		
Pixels in file	1201	1201
Pixel size (degrees)	0.0008333	0.0008333
Estimated pixel size (m) at 59.30 degrees North (i.e. the Norwegian test sites)	92.8	47.4

Table 4.1 SRTM X- and C-band DEM data received from Germany and USA respectively.

It is the *unedited* 3 arc-second ("90 m") C-band data that are evaluated in this report. *Unedited* SRTM C-band 3 arc-second data were released continent by continent in year 2003 and 2004. These data are free of charge and can be obtained over the Internet. Download to FFI was carried out in January 2004. Interested readers may download data themselves [SRTM web page with download of scientific C-band data, 2005].

The names of each data tile of the *unedited* data refer to the latitude and longitude of the lower-left (southwest) corner of the tile (e.g. N59E009.hgt). This follows the DTED convention. To be more exact, these coordinates refer to the geometric centre of the lower left pixel. Each unedited 3 arc-second file is provided as 16-bit signed integer data in a simple binary raster with the filename extension <.hgt> . There are no header or trailer bytes embedded in the file. The data are stored in row major order, and the byte order is "big-endian" with the most significant byte first (i.e. suitable for UNIX systems, but will need byte-swapping for most PCs). Every 3 arc-second data file contains 1201 lines and 1201 samples with overlapping rows and columns to their adjacent cells. This organization also follows the DTED convention.

The projection is geographic (Lat/Lon), but the data are mapped onto the NGA/NASA EGM96 geoid [WGS 84 Earth Gravitational Model, 2005] (i.e. it is using meters above sea level) rather than using the WGS84 ellipsoid. The data will then be directly comparable to digital elevation maps that commonly are referring to the geoid.

4.5 The NGA/NASA EGM96 geoid

The SRTM X-band DEMs were delivered from DLR with the elevation data projected onto the WGS84 ellipsoid. In order to compare the data with digital maps, the X-band DEMs must be converted to geoid heights. This can be done using the NGA/NASA EGM96 geoid model. This geoid model is the one used by JPL for the SRTM C-band DEMs.

Geoid heights based on NGA/NASA EGM96 can be estimated from software obtained from the Internet [WGS 84 Earth Gravitational Model, 2005], see more details in chapter 6.2.

4.6 N50 digital topographic raster maps

The Norwegian Mapping Authority produces the N50 digital topographic raster maps. These maps are based on digital topographic vector data with 20 m elevation contours as well as a road elevation database called VBASE. The digital topographic vector data are the digitised version of the commonly used 1:50 000 paper maps (M711). These maps are made by the Norwegian Mapping Authority.

4.7 N5 digital topographic raster maps

The N5 digital raster maps are produced from the following types of digital vector data: 5 m elevation contours, trigonometric points, spot heights, road heights at certain points, lake boundaries, coastline, rivers and streams. These vector data are the digitised version of the 1:5000 paper maps (economic maps commonly used by the local counties in Norway). The original digital vector data were delivered to this project from the Norwegian Mapping Authority. FMGT interpolated and transformed the elevation vector data into a digital elevation raster format using the WGS84 UTM projection and 5 m pixel spacing.

4.8 IRS-1C satellite image

The Indian satellite (IRS-1C) acquired a multispectral image over the Oslofjorden region in summer 1997. The spatial resolution is approximately 6.8 meters. The image covers the Vestfold test site. The Norwegian Mapping Authority delivered the IRS-1C satellite image to this project.

The 3-channel multispectral IRS-1C image will be useful when interpreting special features discovered during the analysis of the SRTM data sets.

4.9 Landsat Thematic Mapper (TM) satellite images

Two Landsat multispectral images are used in this project. They are covering the two SRTM test sites in Norway and are delivered to this project by Norwegian Military Geographic Service:

- Vestfold test site: Landsat-5, acquired 31 July 1999, scene id = 197/019.
- Bykle test site: Landsat-7, acquired 6 August 1999, scene id = 199/019.

The multispectral (7-channels) Landsat images can very well be used to classify surface cover types (e.g. water bodies, agriculture, forest). This will be important when trying to estimate the SRTM DEM accuracies over agricultural fields and forest areas respectively, but also when estimating in particular how forest stands influence the SRTM DEM heights.

4.10 Aerial photos

There is also a set of aerial photos available. These were taken by FFI in August 1999 and in February 2000. These photos are analogue, and they will only be used in a visual interpretation of selected features. As an example, the aerial photo shown in Figure 7.25 was used to analyse the SRTM DEM data shown in Figure 7.24.

5 CRITERIAS FOR ESTIMATING THE SRTM DEM ACCURACY

The accuracies of the SRTM DEMs are estimated by comparing their elevation values to a digital reference map. The digital reference maps are in raster format and originates from the Norwegian Mapping Authority.

There are basically three major tests that are carried out to verify the SRTM DEM quality:

1) Absolute horizontal accuracy
2) Absolute vertical accuracy
3) Relative vertical accuracy

5.1 Absolute horizontal accuracy

How good is the absolute geographical location (Northing and Easting) of the SRTM DEM? The DTED definition is as follows [DTED Specification 2000]: “The uncertainty in the horizontal position of a point with respect the World Geodetic System caused by random and uncorrected systematic errors. The value is expressed as a circular error at the 90 % confidence level.”

Common ground control points (GCPs) are often used when comparing satellite images with maps. Such GCPs can be rivers, road junctions and deployed points that are accurately measured, e.g. with a differential GPS instrument.

In our situation, we are comparing DEMs, and it will be impossible to find such GCPs. However, the SRTM DEM and reference DEM can be *compared relatively to each other* by applying a cross-correlation technique between the raster data sets. The cross-correlation can be carried out using a 2-dimensional Fast Fourier Transform (FFT). The output from the cross-correlation shows how much the SRTM DEM is shifted (in the Northing and Easting direction) with respect to the reference DEM. This shift will be given with sub-pixel accuracy (i.e. a few meters).

5.2 Absolute vertical accuracy

The DTED definition of the absolute vertical accuracy is as follows [DTED Specification 2000]: “The uncertainty in the height of a point with respect to Mean Sea Level caused by random and uncorrected systematic errors. The value is expressed as a linear error at the 90 % confidence level.”

A measure of the vertical accuracy is commonly provided in the form of the Root Mean Square Error (RMSE) statistics. The RMSE often use test points from GPS measurements, spot elevations, or points on contours from existing source maps. The RMSE of the absolute vertical accuracy (*ava*) is expressed as:

$$RMSE_{ava} = \sqrt{\frac{\sum_{i=1}^{N} \left(y_{true} - y_{model} \right)^2}{N-1}} \tag{5.1}$$

where y_{model} is an elevation point from the DEM under investigation, y_{true} is the reference DEM value (i.e. “true“ value), and N is the number of sample points. The RMSE statistics is essentially a standard deviation and is thus based on the assumption that errors in the DEM are random and normally distributed. In this case, a factor can be used to obtain the 90 % confidence level from the RMSE estimate:

$$90\,\%\,\text{confidence} = RMSE * 1.649 \tag{5.2}$$

In the case of 95 % confidence, the factor 1.96 substitutes 1.649 in the above equation. In this report, $RMSE_{ava}$ is estimated using the SRTM DEMs and the reference DEM for several ground surface cover types.

5.3 Relative vertical accuracy

The SRTM project definition for the relative vertical accuracy stem from the C-band swath width and require that the height errors have an arbitrary mean and a variation of 6 m (90 % confidence level) within a 225 x 225 km large area. This specification assures that a user can easily correct his area of interest by adding a single corrective height value [Rabus *et al.* 2003].

The relative vertical accuracy is also called *point-to-point accuracy*. The DTED definition is as follows [DTED Specification 2000]: “The uncertainty in height between two points caused by random errors. The value is expressed as a linear error at the 90 % confidence level.”

The relative vertical accuracy of a dataset is especially important for derivative products that make use of the local differences among adjacent elevation values, such as slope and aspect calculations. Reference points for doing this point-to-point evaluation should therefore be collected at the top and bottom of uniform slopes, see illustration in Figure 5.1.

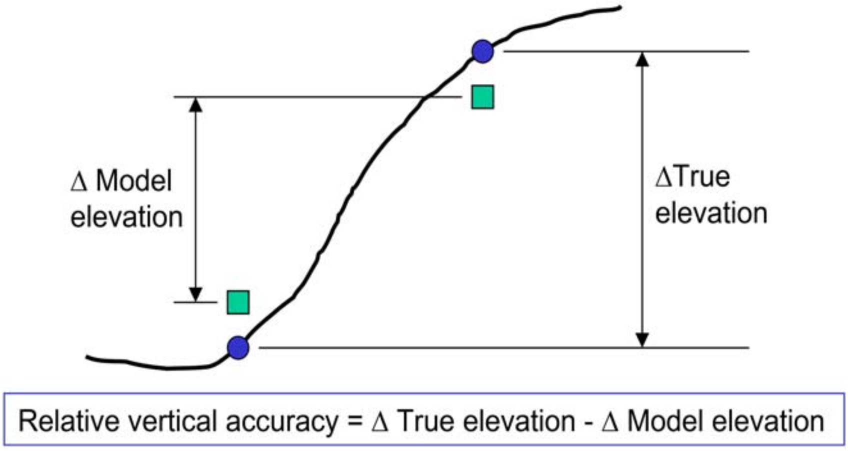


Figure 5.1 Illustration of the relative vertical accuracy estimate.

The RMSE of the relative vertical accuracy (*rva*) is then given as:

$$RMSE_{rva} = \sqrt{\frac{\sum_{i=1}^{N}\left(\Delta y_{true} - \Delta y_{model}\right)^2}{N-1}} \qquad (5.3)$$

where Δy_{model} is the difference in elevation between two points in the DEM under investigation, and Δy_{true} is the elevation difference between two reference DEM values (i.e. “true“ values). N is the number of difference samples. The relative vertical accuracy of a DEM is normally better (i.e. a smaller value) than the absolute vertical accuracy of the same DEM.

The present SRTM dataset over the two Norwegian test sites are limited in size. The relative accuracy can therefore not be estimated from several 225 x 225 km large areas. Instead, adjacent DEM points are used together with equation *(5.3)*. Now, we also know that the SAR sensors onboard the Shuttle were viewing the test sites in Norway from more or less one direction – from the south. In order to see if there are any relative vertical error dependencies on the radar viewing geometry, we evaluate adjacent points in three directions: Northing, Easting and diagonal. Results from the estimated relative vertical accuracy are given in chapter 7.6.

6 PREPROCESSING

6.1 Description of the analysis methodology

The analysis methodology is governed by the format, quality and type of data available. As described in another section, there are several data sources available: digital maps, SRTM data sets, satellite images, and aerial photos (analogue).

First, all the digital data sets were transformed into the same coordinate system. The SRTM DEM data are originally projected in the geographic coordinate system (latitude/longitude using WGS84). The optical satellite image data and reference maps are all transformed into this projection before the analysis is carried out.

It is then possible to quite simply estimate the accuracy of the SRTM data using the reference maps. However, we know that the SRTM elevations are defined with respect to the reflective surface computed from the interferometric SAR returns from the Earth features. This means that the SRTM elevations may show the ground elevations in bare agricultural landscape, but that the elevations may partly come from the tree canopies in dense forest regions. It is therefore of interest to separate the test area into a few major surface classes before running the evaluation of the SRTM DEM. A surface cover classification can be performed using the available Landsat TM data set.

It is unknown if there is a small elevation offset (bias) in the C-band and X-band SRTM DEMs. The data are tested for any offset by comparing the SRTM DEM with reference values. Subsequently, it is possible to correct for any elevation bias prior to applying the statistical tests (e.g. RMSE).

The high quality reference DEM (N5) is only available for the Vestfold test site, while the coarser reference DEM (N50) is available for both the Vestfold and Bykle test sites. Before using the N50 data as the reference map in the mountainous Bykle region, it is worth estimating its overall vertical elevation accuracy. The RMSE between the N5 and N50 maps over the Vestfold test site is therefore estimated. It is assumed that the N5 data is the “truth”. Errors discovered by this test should be taken into account when interpreting the results from the SRTM DEM analysis over Bykle.

The Bykle test area consists of mountainous terrain with rolling topography and steep slopes. The forest in the area is very sparse. This area is therefore suited to test the limitations of the side-looking SRTM mapping geometry. We expect to find areas that will be in shadow from the Shuttle imaging radar sensor. In addition, extreme geometric distortions will introduce errors in the SRTM DEMs.

The SRTM DEM data sets are accompanied by data that tells the user that there may be errors in the DEM due to interferometric SAR processing limitations:

- The SRTM C-band DEM marks certain raster cells with the value –32768 and calls these points “*void data*”.
- The SRTM X-band DEM comes with an additional file called Height Error Model (HEM). The values here indicate the uncertainty (in meters).

The HEM values should be analysed with respect to the reference DEM, as well as the SRTM C-band DEM. It will also be of great value to find out the limitations of the SRTM viewing geometry (i.e. under which relief and slope conditions the C-band DEM will indicate “void data”).

6.2 Using a common Earth geoid model

The digital maps used in this project all reference their elevation heights to the geoid (mean sea level). The SRTM X-band DEMs that were delivered to FFI are all projected onto the WGS84 ellipsoid. The data must therefore be transformed to the local geoid.

The geoid heights in Norway are between 18 and 48 meters above the WGS84 ellipsoid. The difference between the ellipsoid height e_h and the height above mean sea level h_{sea} (the geoid) is called the geoid height, g_h :

$$g_h = e_h - h_{sea} \tag{6.1}$$

The geoid heights vary from 39-41 m and 44-46 m above the WGS84 ellipsoid for the Vestfold and Bykle test sites respectively.

The new height above the geoid h_{sea} can be calculated for the SRTM X-band DEM if the geoid height g_h is known. This calculation may be carried out using two geoid models:

- A local model used by the Norwegian Mapping Authority.
- The global NGA/NASA EGM96 Earth Gravity Model [WGS 84 Earth Gravitational Model, 2005].

The SRTM C-band elevation data are projected onto the geoid using NGA/NASA EGM96. It is therefore attractive to use this model to also correct the SRTM X-band DEM. However, will there be large differences between the Norwegian and EGM96 model? This question is answered by estimating the root mean square error (RMSE) between the two models over some points located within the two test areas. Results show an RMSE of 0.2 m and 0.5 m for the Vestfold and Bykle test sites respectively. These errors are relatively small. We therefore decided to use the NGA/NASA EGM96 geoid model in the evaluation process described in this report.

Software to estimate a geoid model based on the NGA/NASA EGM96 was downloaded for free from an Internet site [WGS 84 Earth Gravitational Model, 2005]. After some minor editing and compilation of these Fortran programs, it was possible to estimate the geoid for the two SRTM test sites in Norway. The result was saved to two raster files with the same geographic (Lat/Lon) projection and pixel spacing as the SRTM X-band DEM. Equation (6.1) was then finally applied to the geoid model and the original SRTM X-band DEM in order to obtain the new SRTM X-band DEM values that reference their heights to the geoid (i.e. mean sea level).

6.3 A common map coordinate system

The SRTM DEMs are all given in the geographic (Lat/Lon) projection, while the digital maps, optical satellite images and the SRTM X-band SAR images are given in the UTM projection.

The main task in this project is to evaluate the SRTM DEMs. We therefore decided to keep the SRTM DEMs in their original form to avoid introducing resampling errors. Consequently, the digital maps and optical satellite images were transformed into the geographic (Lat/Lon) projection with a pixel spacing defined by the SRTM DEMs. This transformation was carried out using resampling with bi-cubic interpolation.

The Landsat TM data were resampled to geographic coordinates (Lat/Lon) *prior* to applying the surface cover classification routine (ISODATA), see chapter 6.8 for more details.

6.4 Errors in the N5 raster DEM

The present N5 elevation raster dataset was produced by FMGT from N5 vector data delivered by Norwegian Mapping Authority. After producing the raster map, it became clear that a lot of errors were present:

- Parts of contours had wrong elevations
- Full contours had wrong elevation
- Height points had obviously wrong elevation (tens of meters error)
- Road elevation points had wrong elevations

FMGT removed some of the obvious errors, and processed a second N5 raster that was delivered to FFI in June 2004. The author at FFI carried out further corrections by editing the vector dataset. Some of the errors were checked up with the original 1:5000 paper maps. This indicated that even the paper maps have got the wrong numbers in places! Most contour errors could be corrected for by comparing with surrounding elevation contours, as they normally will increase or decrease in steps of 5 m. However, several height points and road elevation points were just excluded from the database for simplicity. A full list of the 80 corrections performed at FFI can be found in APPENDIX A.2. After these corrections in the vector database, FMGT produced a third N5 raster map in summer 2004. It is *this* N5 raster map that is used in the present SRTM analysis.

Originally, this N5 raster DEM has a pixel spacing of 5 m using WGS84 with UTM zone 32. The N5 data is resampled to geographic coordinates and a pixel spacing of “30 m” or “90 m” before it is used in the analysis of the SRTM DEM accuracies.

6.5 Errors in the N50 raster DEM

The N50 raster DEM will in general be within the DTED-2 specifications (see chapter 6.6). However, as pointed out earlier [Sagstuen 2003], the N50 raster will not capture essential topographic variations along rivers and streams cutting through an agricultural landscape. Investigations along such features show that the N50 DEM may give elevations that are 9-13 m higher than the N5 DEM, see Figure 6.1.

Similarly, small tops on forested hillsides may not be captures, but the N50 will show elevations that are 11-14 m lower than the truth. Thus, one may say that the N50 data are *low-pass filtered* when compared to the higher quality N5 data.

Another inaccuracy in the N50 raster dataset is that small hillsides having height elevations less than 20 m with respect the surrounding terrain will not be captured! This is because the N50 raster is based on elevation contours with 20 m equidistance. A typical example from Jarlsberg in Vestfold is shown in Figure 6.2.

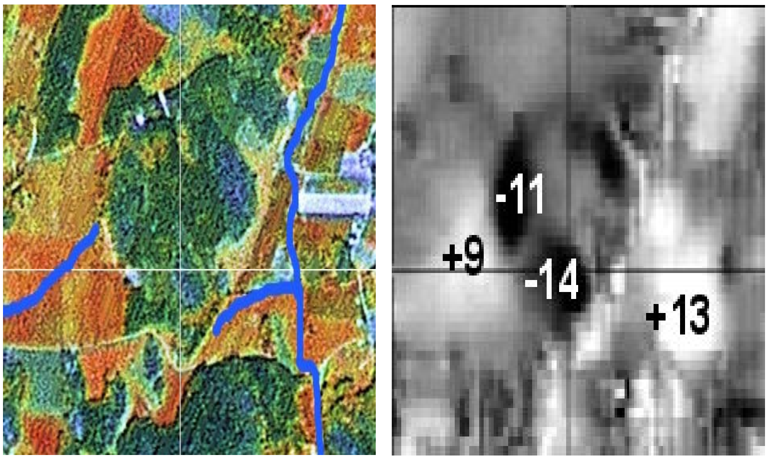


Figure 6.1 Agricultural area with a small, forested hillside south-east of Torp Airport, Vestfold. IRS-1C image with streams indicated (left). N50 error map (right). The grid spacing of the DEM is approximately 30x15 m. The higher elevations registered by the N50 map along rivers and streams are leading to errors in the order of 9 to 13 meters (represented as white tone in the right image). Similarly, small tops on the forested hillside are not captured (dark grey/black), but errors of -11 and -14 meters are introduced. (IRS-1C image: © Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997.)

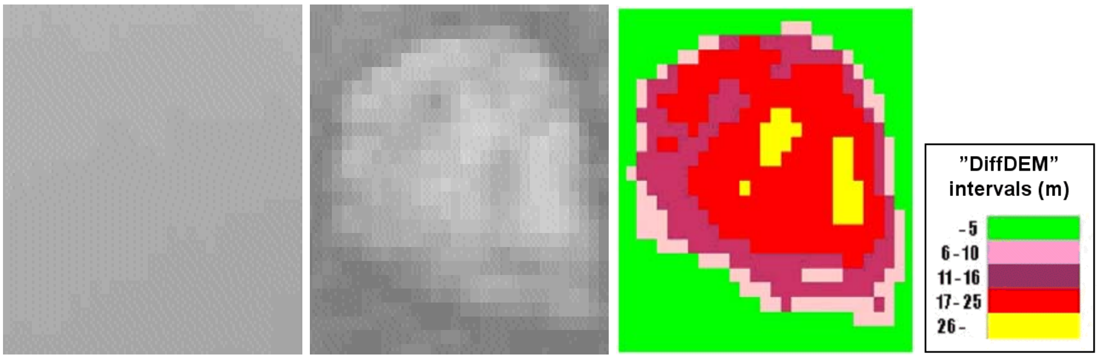


Figure 6.2 The SRTM X-band DEM (middle image) shows a forest-covered hill in midst of a relative flat agricultural landscape at Jarlsberg, Vestfold (see forest area A in the aerial photo in Figure 7.18) . This hill is not present in the N50 raster dataset (left image). The difference between the two DEM datasets is shown in colour (right image). Comparison with the N5 elevation data shows that the hill is 12 m higher than the surrounding terrain. The elevations up to as much as 25 m in the difference map (right) indicate that the dense deciduous forest will model the X-band DEM heights to a higher elevation than the true ground. From [Sagstuen 2003].

Another effect that may occur in the N50 raster DEM is that flat agricultural fields may be slightly lower than the actual terrain *close to* small hills. This comes from the fact that the interpolation routine that is used to convert the vector data to raster may not be able to handle abrupt changes and discontinuities. This may lead to "overshoot" or "undershoot". Although the data itself still are within the DTED-2 specifications, the result will be inaccuracies in the raster DEM in a relatively uncomplicated terrain. Better interpolation routines could possibly compensate for this (e.g. using a set of "model" kernels), but this is a research topic outside the scope of this study.

6.6 Comparison of the N5 and N50 reference DEM

There are two elevation data sets available for this SRTM project in Norway: N50 raster and N5 raster. The N50 raster covers all land surfaces in Norway, while the N5 raster only covers regions with agricultural fields, forested areas, urban, and infrastructure. The result is that Vestfold County is covered by the both the N50 and N5, while the mountainous Bykle test area is only fully covered by the N50 data set.

Tests reported by FMGT in 2003 show that the N50 elevation raster data over Norway (also called DTED-2 in FMGT terminology) has a height difference (relative to N5 elevation data) that is less than 18 m for 95.9 % of 52 000 000 sample points evaluated from 12 different Norwegian test sites. The N50 raster data is therefore within the DTED-2 specifications.

The accuracy of the N50 raster DEM was also investigated in this SRTM-project. Agricultural fields in Vestfold County are used with the N5 raster DEM as reference data. Results give an RMSE of 5.0 m with a calculated 90 % confidence level of 8.2 m (“calculated” means that the 90 % confidence level is obtained by using RMSE*1.649, see section 5.2). This is better than the results reported by FMGT above (who probably used a variety of terrain types in their analysis), but as we shall see later (chapter 8.1), is still poorer than what is obtained for the SRTM DEMs over the same agricultural fields.

The Master Thesis work that was carried out over Vestfold in 2003 [Sagstuen 2003] used the N50 raster data since the N5 raster was not available at that time. This Master Thesis clearly demonstrated that the SRTM X-band DEM was able to show more details than the N50 raster.

6.7 Making a land surface topography mask over Vestfold

The sea surface and lakes are not masked in the present SRTM DEM data sets. This means that height variations may very well be present at water bodies. In fact, low SRTM SAR backscatter from such surfaces may introduce errors of the order of tens of meters. In order to get a proper statistical estimate from areas of land surface topography, it is best to mask out the water bodies.

In this project, we have access to lakes and sea surface boundaries through the digital N5 vector database. These data were converted from vector to raster, and then resampled to the SRTM DEM geographic (Lat/Lon) projection.

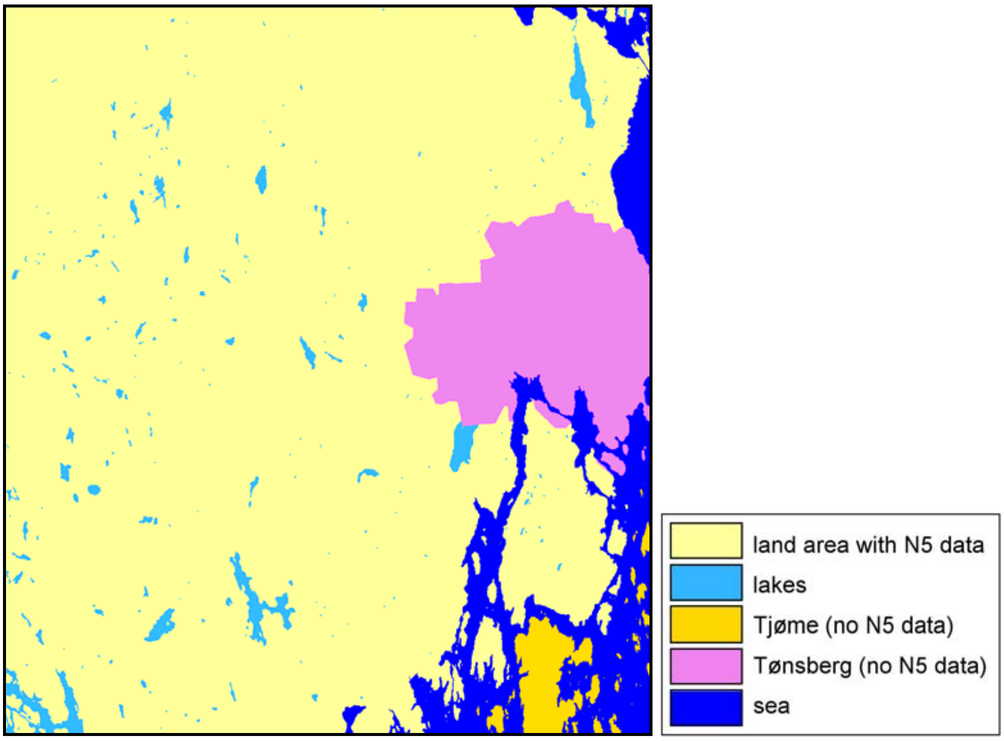


Figure 6.3 The land surface topography mask covering the Vestfold test site.

The N5 topographic raster data will be used extensively in this project to validate the SRTM DEMs in Vestfold. However, N5 data are missing from the Tjøme and Tønsberg local counties that are part of the SRTM test site in Vestfold. The boundaries of these local counties should therefore also be masked to avoid running the analysis into *not-available* data regions. The resulting land surface topography mask is shown in Figure 6.3.

6.8 Making a vegetation mask over Vestfold

It is expected that dense forest areas will model the SRTM DEMs, especially in X-band (see chapter 2.5). This means that the SRTM DEM may show slightly higher elevations over forest stands than what is found over agricultural fields nearby. It will therefore be of great value to distinguish between agricultural land and forest areas in the SRTM DEM analysis.

The multispectral Landsat-5 image from 31 July 1999 is used to obtain a land cover mask. This satellite image is first transformed to the SRTM DEM geographic (Lat/Lon) projection. An unsupervised ISODATA classifier is then applied on the six multispectral bands (1, 2, 3, 4, 5 and 7). This ISODATA routine is executed using 20 classes, 10 iterations and a convergence threshold of 95 %.

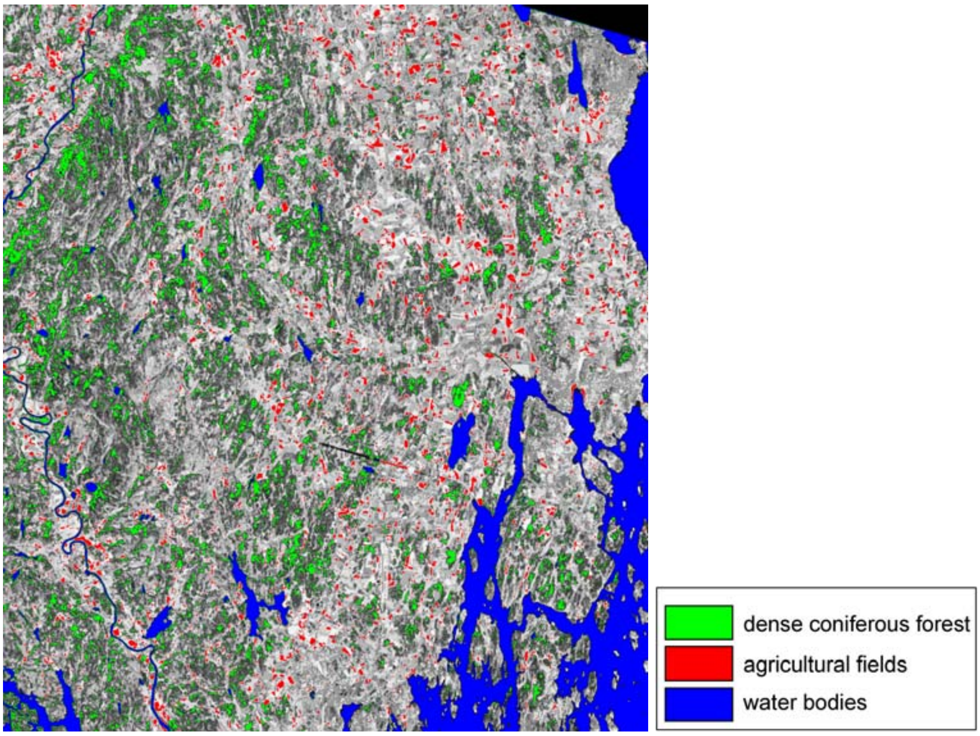


Figure 6.4 Result of applying ISODATA clustering on the Landsat TM image covering the Vestfold test site. The class agricultural field and dense coniferous forest are shown in red and green colours respectively. Water bodies are shown in blue colour, while the 17 other clusters are shown in shades of grey.

The ISODATA clusters were then investigated and compared with the multispectral IRS-1C image as well as maps and aerial photos. The result shows that it is not possible to extract *all* agricultural fields from a given set of clusters. Rather, several clusters are *a mixture* of agricultural fields, marsh, built-up areas and small forest stands. The reason for this is probably that a lot of green vegetation at the agricultural fields at this time of year are mixed up with other surface classes. The ISODATA routine was also executed again using 25 and 30 classes, but no significant difference was obtained.

However, it is still possible to use this result, as there seem to be two clusters that definitely can be categorized to the class agricultural fields (class 20) and dense coniferous forest (class 3) respectively. The result of the ISODATA clustering is shown in Figure 6.4, and the class agricultural field and dense coniferous forest are shown in red and green colours respectively.

6.9 Degrading the X-band DEM to the C-band DEM sampling

Some of the analysis was best carried out using similar raster spacing of the SRTM DEMs. In these cases, the X-band DEM (approximately 30x15 meters) was transformed to the “90 m” C-band DEM raster spacing (approximately 90x45 meters) using a 3x3 block averaging.

6.10 Estimating vertical bias in the SRTM DEMs

The SRTM DEMs are generally corrected for any vertical bias (offset) by the processing facilities (JPL in USA and DLR in Germany). The SRTM data are calibrated using ground control points (GCPs), coastlines, and the GLOBE digital elevation model having a grid of 1 km.

It is reported that the absolute elevation difference between the X- and C-band data are less than +/- 6 m for much of the globe, and that a mean difference value of –0.89 m is found for Europe [Marschalk *et al.* 2004].

A vertical bias can be estimated for the SRTM DEMs by comparing with the following reference sources:

- N5 elevation data from agricultural fields.
- Elevations at corner reflector positions.
- Elevations found over sea/fjord/lake.

After correcting for any vertical bias, it is possible to estimate the general vertical accuracy of the SRTM DEMs for various ground surface types.

7 RESULTS FROM VESTFOLD

7.1 Evaluating the X-band HEM

The “30 m” SRTM X-band DEM from the Vestfold test area in Norway is shown in Figure 7.1. DLR will normally deliver a separate height error map (HEM) product together with the DEM. The HEM product is evaluated underneath.

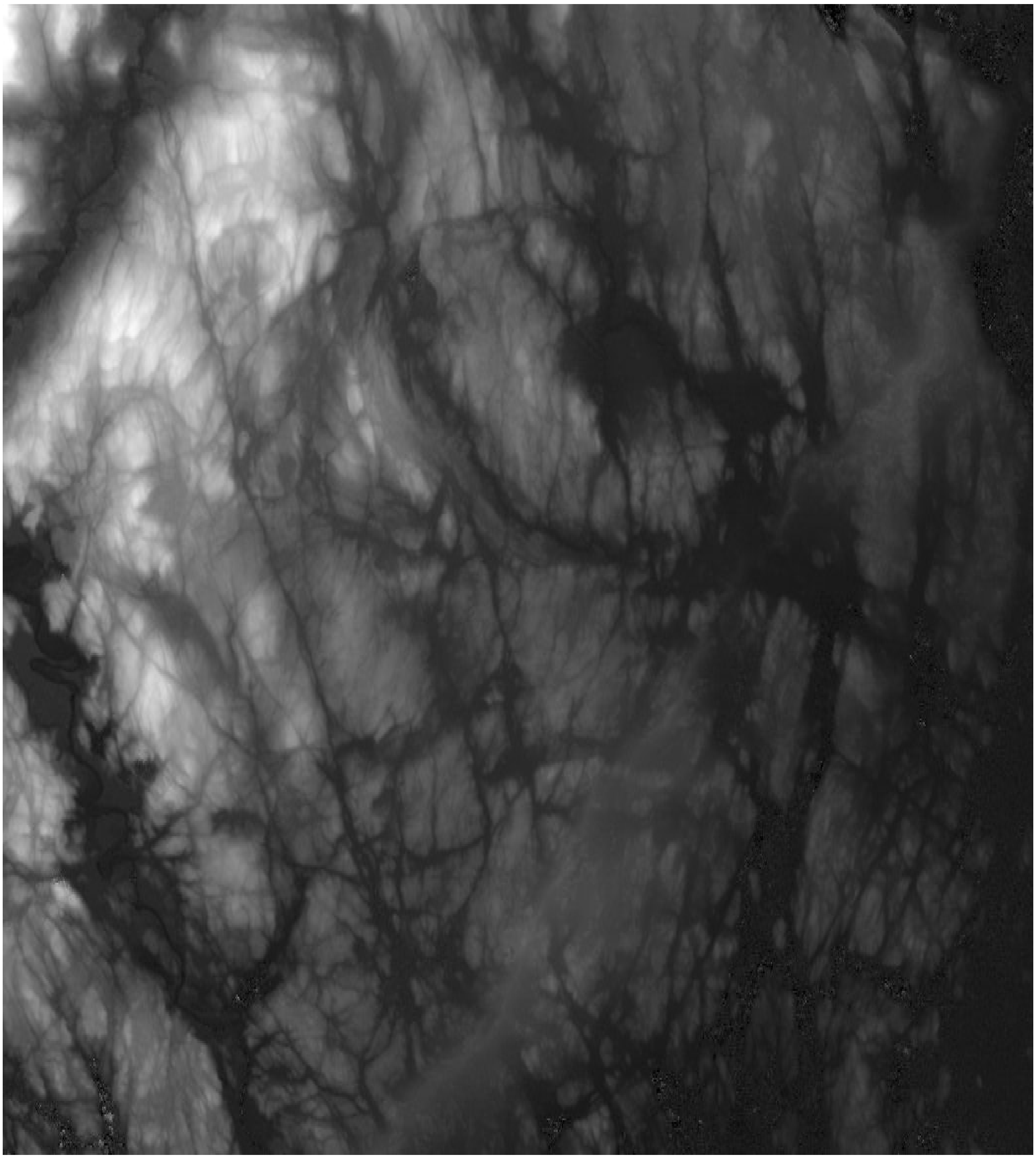


Figure 7.1 SRTM X-band DEM from the Vestfold test area. The above DEM covers an area of approximately 36.9 km (North) x 33.0 km (East). The present X-band DEM has a pixel spacing of approximately 30 m x 15 m in the Northing and Easting directions respectively. (© DLR 2003.)

7.1.1 HEM in multi-pass regions

The SRTM X-band SAR system was able to cover the same area several times at the very northern latitudes. This is clearly seen from the map in Figure 7.2 where the SRTM X-band SAR acquisitions from south Norway are marked.

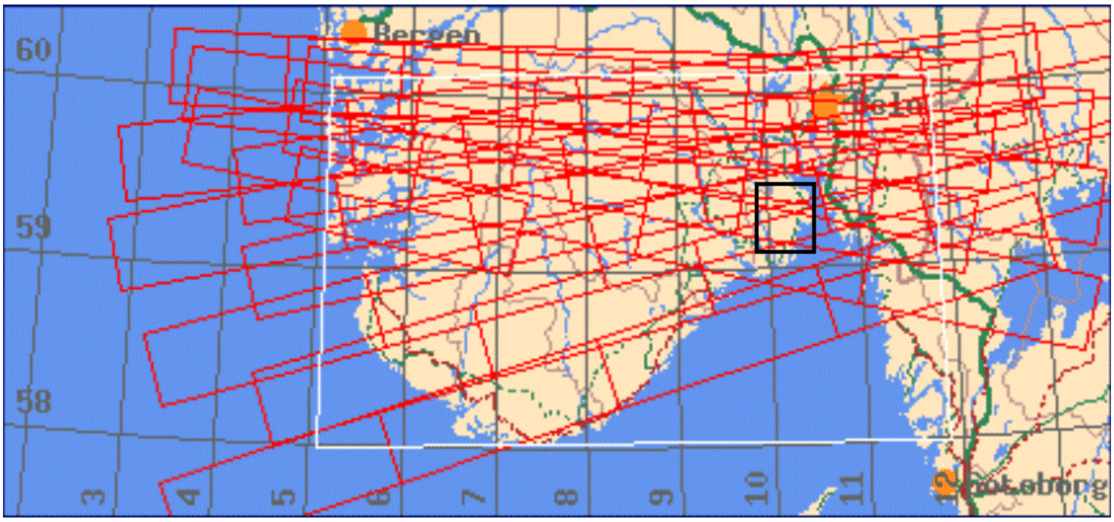


Figure 7.2 SRTM X-band SAR acquisitions covering the southern part of Norway. The Vestfold test area is marked with a black square. The map is a 'screen dump' taken from the DLR EOWEB.

Now, both DLR and JPL are using not only one, but all available SRTM acquisitions from the same SAR sensor to produce their final DEM products. This is done by first processing the SAR interferograms for every swath. Then an *incoherent averaging* of the interferograms is carried out to produce the final DEM. It is known that incoherent averaging over several SAR acquisitions will bring the errors down. The number of overlapping acquisitions over the same geographic area will therefore have a direct impact on the accuracy of the final SRTM DEM.

The SRTM X-band DEM from the Vestfold test area is shown in Figure 7.1. The corresponding X-band HEM is shown colour-coded in Figure 7.3. When comparing this HEM with the SRTM X-band SAR swaths in Figure 7.2, it is clear that the HEM values seem to be larger (i.e. larger height errors) in the regions covered by only two SRTM X-band SAR passes (one ascending and one descending), as compared to those regions covered by four passes (two ascending and two descending).

The HEM from the "2-pass" region (i.e. the region marked "A" in Figure 7.3) is shown in Figure 7.5 together with the SRTM X-band SAR image data. Similarly, the "4-pass" region is shown in Figure 7.6 together with the SAR image data. We can now perform a visual comparison of the HEM data and the SAR images. It seems to be clear that the low HEM values are located in areas with relatively *high* SAR backscatter. On the contrary, the high HEM values are found at places with *low* SAR backscatter, - typically water bodies or runways. These findings seem to be independent of vegetation type (i.e. forest or agricultural fields). However, one should notice that agricultural fields might give HEM-values up to 5 m in the 4-pass region in the presence of particularly low SAR backscatter.

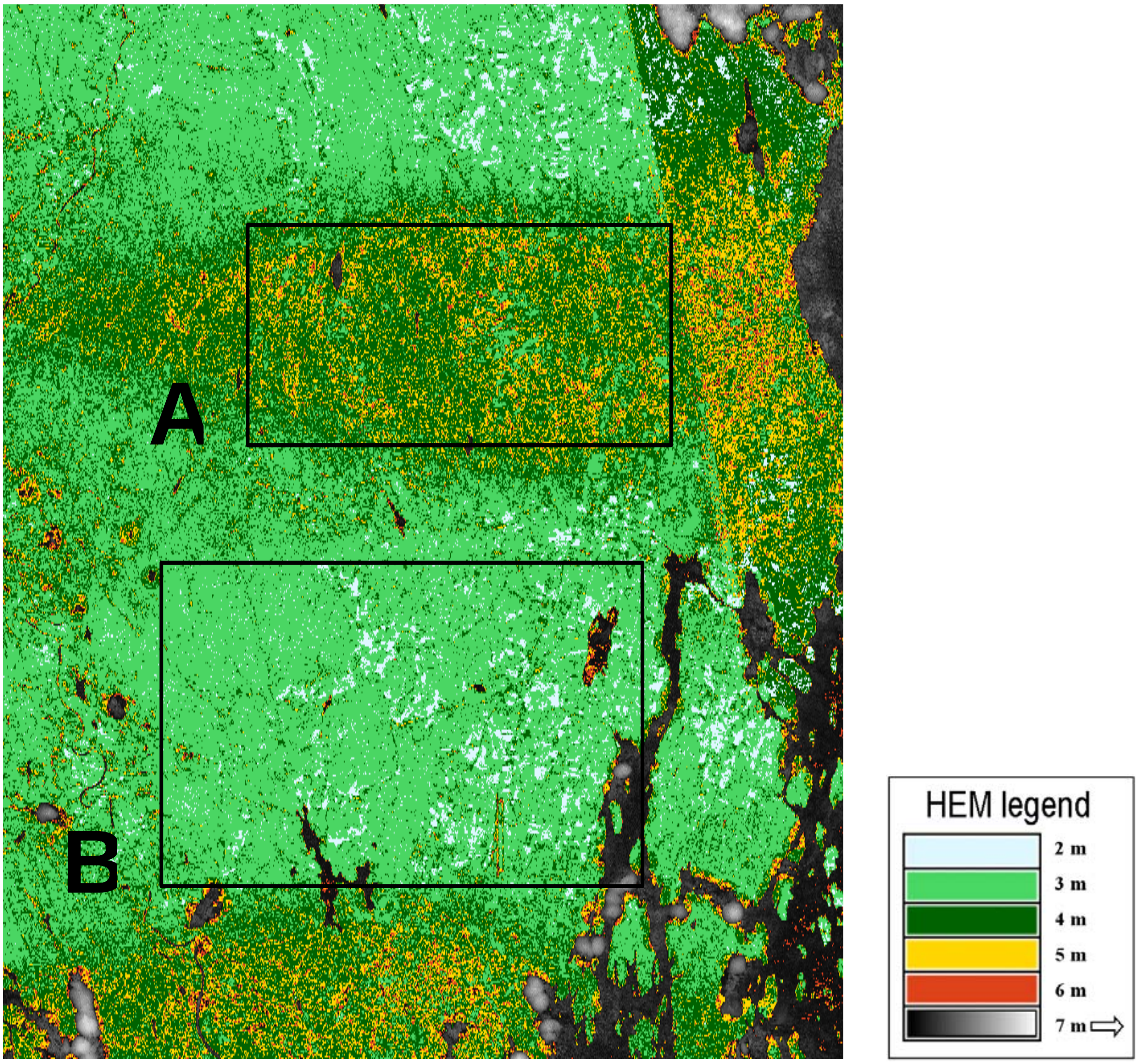


Figure 7.3 *Colour-coded SRTM X-band HEM from the test area in Vestfold. The region labelled 'A' is where the HEM-values are estimated from 2 acquisitions, while the 'B' region has HEM-values estimated from 4 acquisitions. (HEM data: © DLR 2003.)*

Figure 7.4 shows some interesting features. Circular patterns of relatively high HEM values are seen around a couple of lakes, but also in a fjord. Clearly, the SRTM InSAR processing filter has limitations in the presence of spots with large height errors. One should also note that the runway has a higher elevation uncertainty than the surrounding fields! This is caused by the low SAR backscatter from the concrete surface.

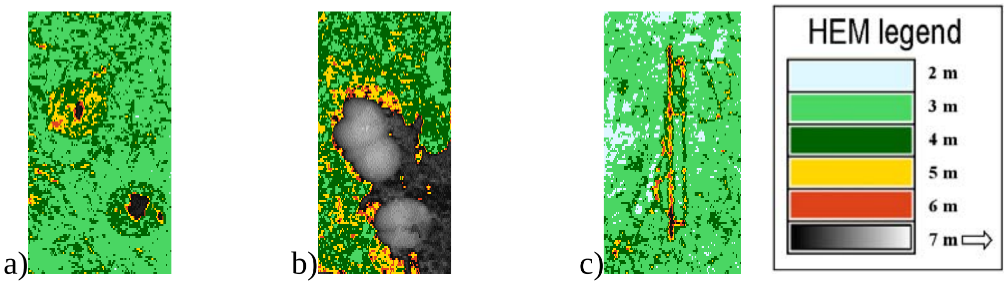


Figure 7.4 Three regions showing the following features: a) circular features of relative high HEM values around two lakes b) circular features of high HEM values at the ice-covered water surface in the fjord c) relative high HEM values from the runway and taxiways at Sandefjord Airport Torp

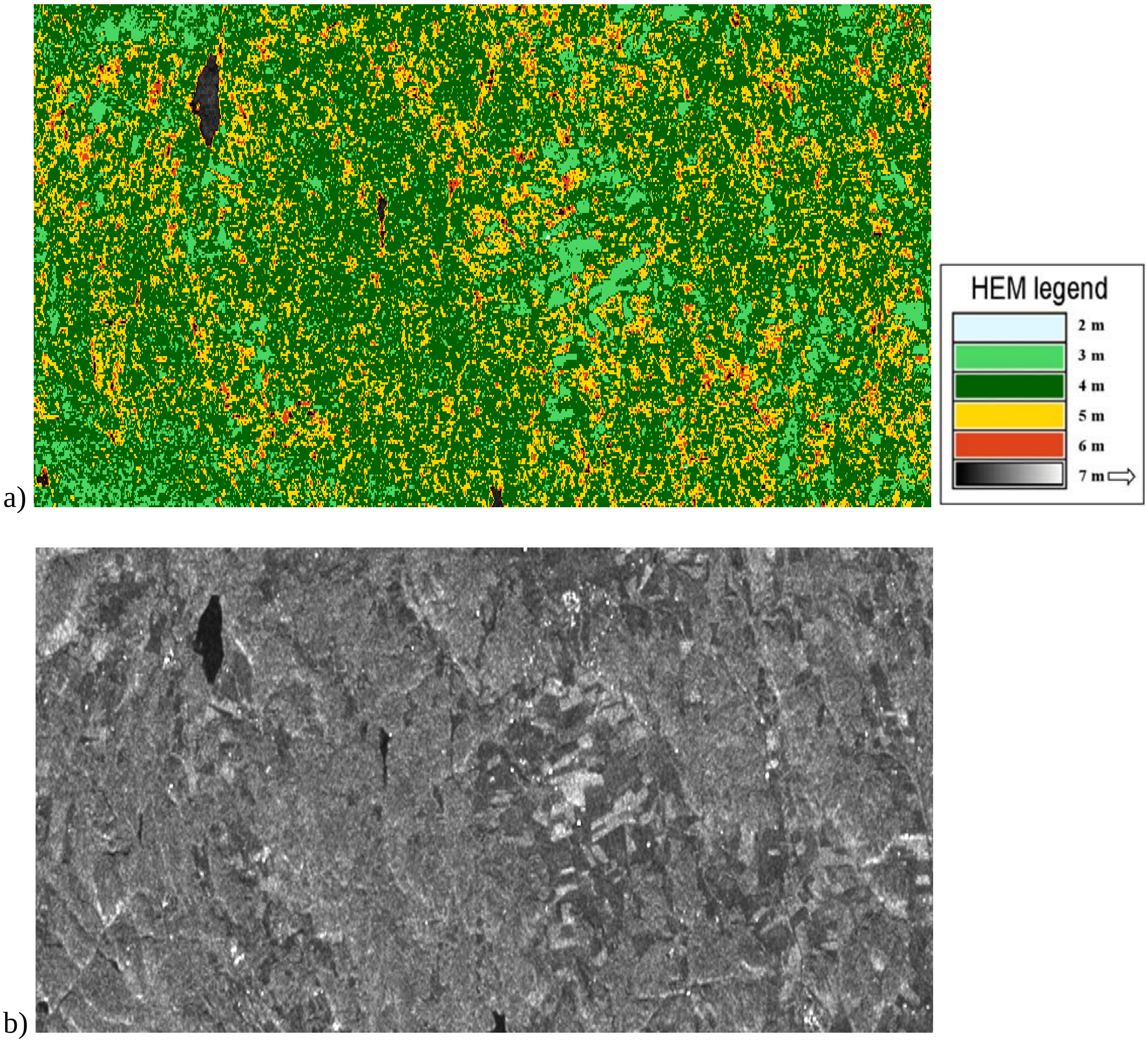


Figure 7.5 a) Colour-coded height error map (HEM) from a region in Vestfold with two SRTM X-band acquisitions (HEM data: © DLR 2003). b) A SAR image showing the average of two SRTM X-band SAR geocoded terrain corrected (GTC) images acquired the 14 and 16 February 2000 (© DLR 2003).

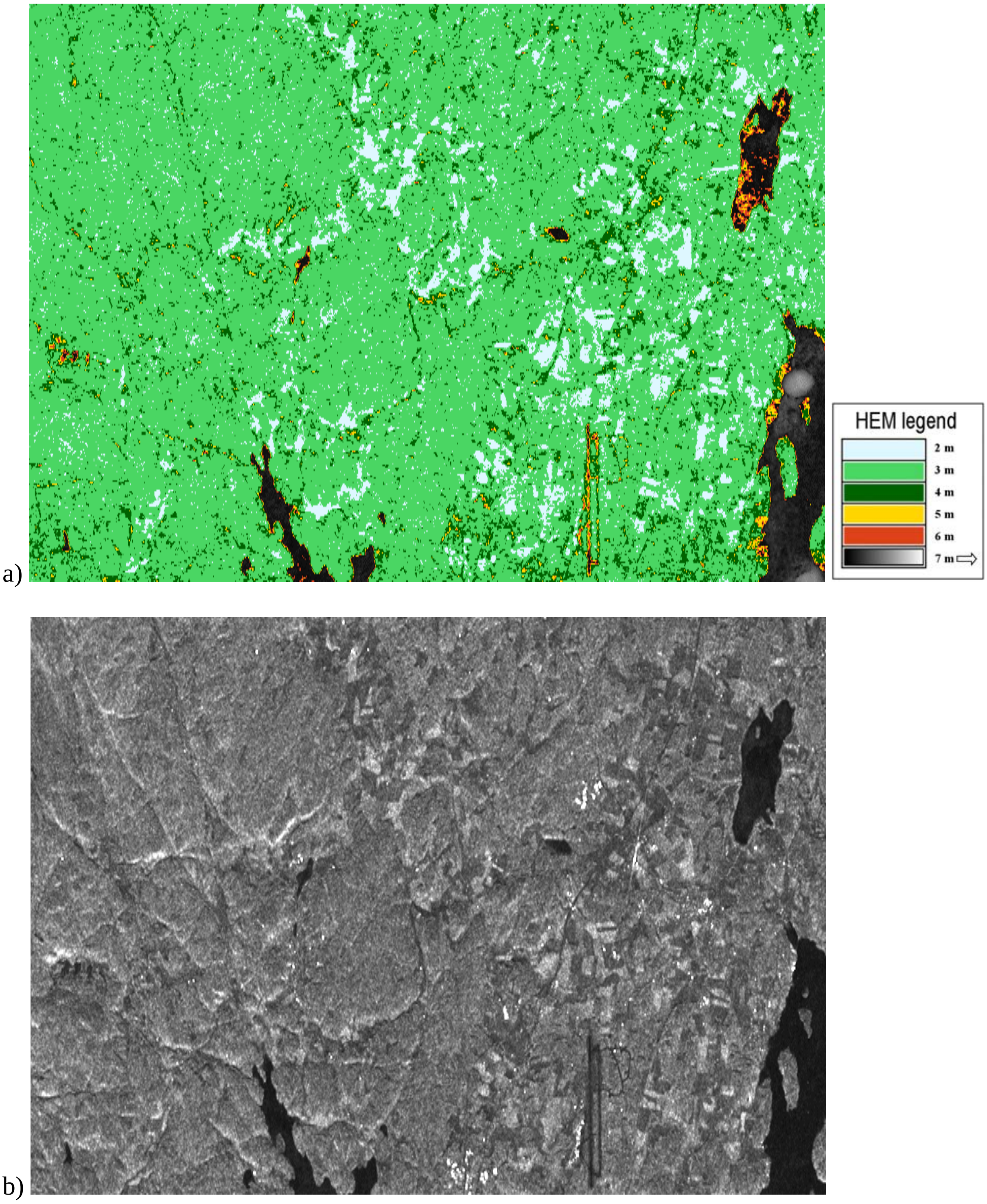


Figure 7.6 a) Colour-coded height error map (HEM) from a region in Vestfold with four SRTM X-band acquisitions (HEM data: © DLR 2003). b) A SAR image showing the average of two SRTM X-band SAR geocoded terrain corrected (GTC) images acquired the 14 and 16 February 2000 (© DLR 2003).

7.1.2 HEM statistics

In this section, we calculate HEM statistics with respect to surface cover types and number of passes (i.e. SAR acquisitions).

Figure 7.7 shows the HEM histograms for agricultural fields for both the 2-pass and 4-pass region in the Vestfold data set. The mean HEM value from agricultural fields in the 4-pass region is only 3.03 m, and 99.3 % of the HEM values over the agricultural fields have a value of 4 m or less. The same numbers for the 2-pass region is 4.2 m and with 95.3 % of the samples within 5 m. Clearly, the 2-pass region gives a larger spread of HEM values for the same surface cover type. More histograms can be found in Appendix A.3.

Figure 7.8 shows two HEM histograms for sea and lakes respectively. The majority of HEM values are above 7 meters, with a one standard deviation more than 13 m.

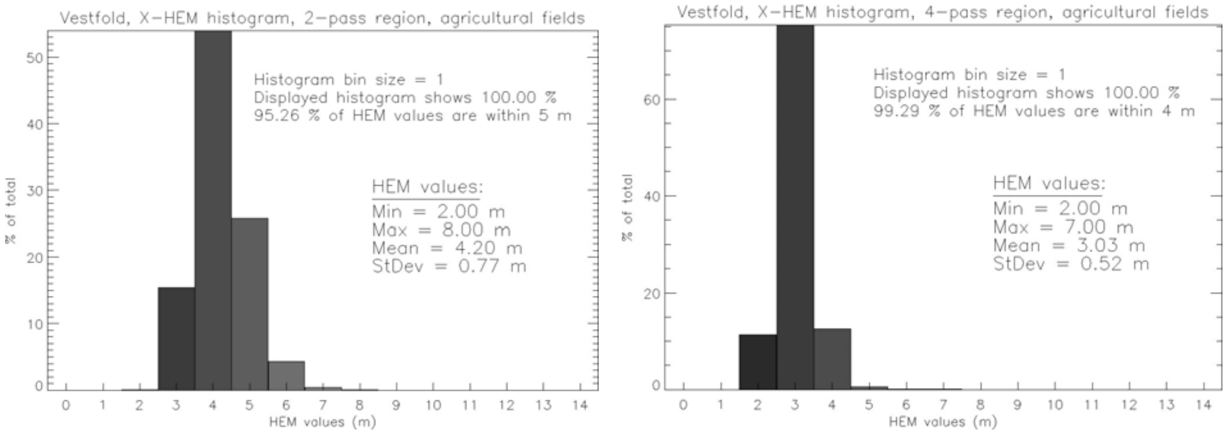


Figure 7.7 SRTM X-band HEM histogram for agricultural fields in the <u>2-pass</u> (left) and <u>4-pass</u> (right) region of Vestfold.

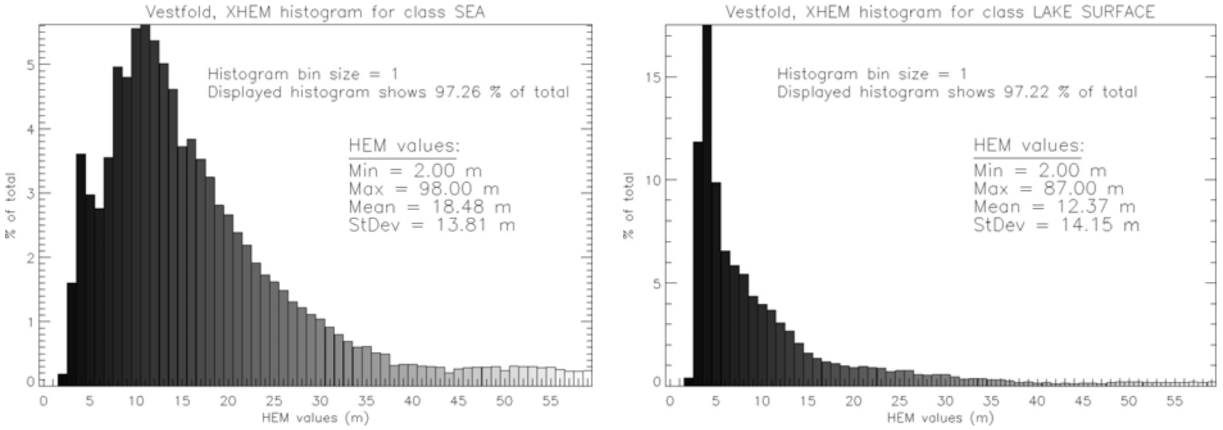


Figure 7.8 SRTM X-band HEM statistics for sea (left) and lake surfaces (right). Note that some lakes may have been covered by ice since the temperatures were below freezing during the SRTM acquisitions in February 2000.

Now, is it possible to link the SRTM X-band HEM value directly to uncertainties in the X-band DEM? In order to answer this question, some first order statistics are calculated for several HEM values over agricultural fields in Vestfold based on the X-band DEM and N5 map. Agricultural fields were chosen as the surface cover class since it is expected that the errors here are more directly linked to the SAR system, and are not affected by surface cover heights (as will be the case for dense forest).

Results from agricultural fields covering the *whole* Vestfold test area (i.e. including *both* the 2-pass and 4-pass regions marked on Figure 7.3) are shown in Table 7.1. (Separate results from the 2-pass and 4-pass regions are given in Appendix A.4)

HEM value in all Vestfold test area	**RMSE [m]**	**Mean diff. [m]**	**St.Dev. [m]**	**Min. [m]**	**Max. [m]**
2	3.10	-2.22	2.17	-12.82	11.94
3	3.52	-1.09	3.34	-17.22	20.22
4	3.78	-0.78	3.70	-14.84	22.95
5	4.14	-0.68	4.09	-11.78	25.79
6	4.68	-0.38	4.67	-13.21	21.78
Average	*3.84*	*-1.03*			

Table 7.1 SRTM X-band DEM statistics calculated from agricultural fields found all over the Vestfold test area. The N5 map is used as the reference.

From the numbers in Table 7.1 one may conclude:

- It is clear that the one standard deviation error increases slightly with increasing HEM values.
- As a rule of thumb, the HEM value corresponds roughly to the one standard deviation error (in meters).
- From the colour-coded HEM-values in Figure 7.3 and the HEM histograms in Figure 7.7 and Appendix A.3, it is clear that nearly all land-covered areas in Vestfold (when excluding water bodies) will have a HEM value ≤ 6 m. Let us assume a normal distribution. It is then possible to use equation *(5.2)* to estimate the 90 % confidence level. From Table 7.1, a HEM value of 6 m would then give: 4.68*1.649 = 7.7 m. This is well within the specifications of +/-16 m for 90 % of the samples. Thus, if we like to use the HEM as a mask, a value of 6 should give a result that is *well* within the DTED-2 specifications. A higher HEM threshold could in fact have been chosen, but as far as the data set from Vestfold is concerned, there are very few land cover type pixels with HEM values greater than 6. However, for mountainous regions the situation is slightly different, as discussed in chapter 8.

The X-band SAR backscatter histograms are shown as a function of particular HEM values in Figure 7.9. As seen, the X-band DEM uncertainty (and hence the HEM value) will *decrease* with *increasing* SAR backscatter level. This will be so, not only for the agricultural surface class, but also for urban and forest areas. More SAR backscatter histograms are presented in Appendix A.5 and A.6 for the 2-pass and 4-pass regions respectively.

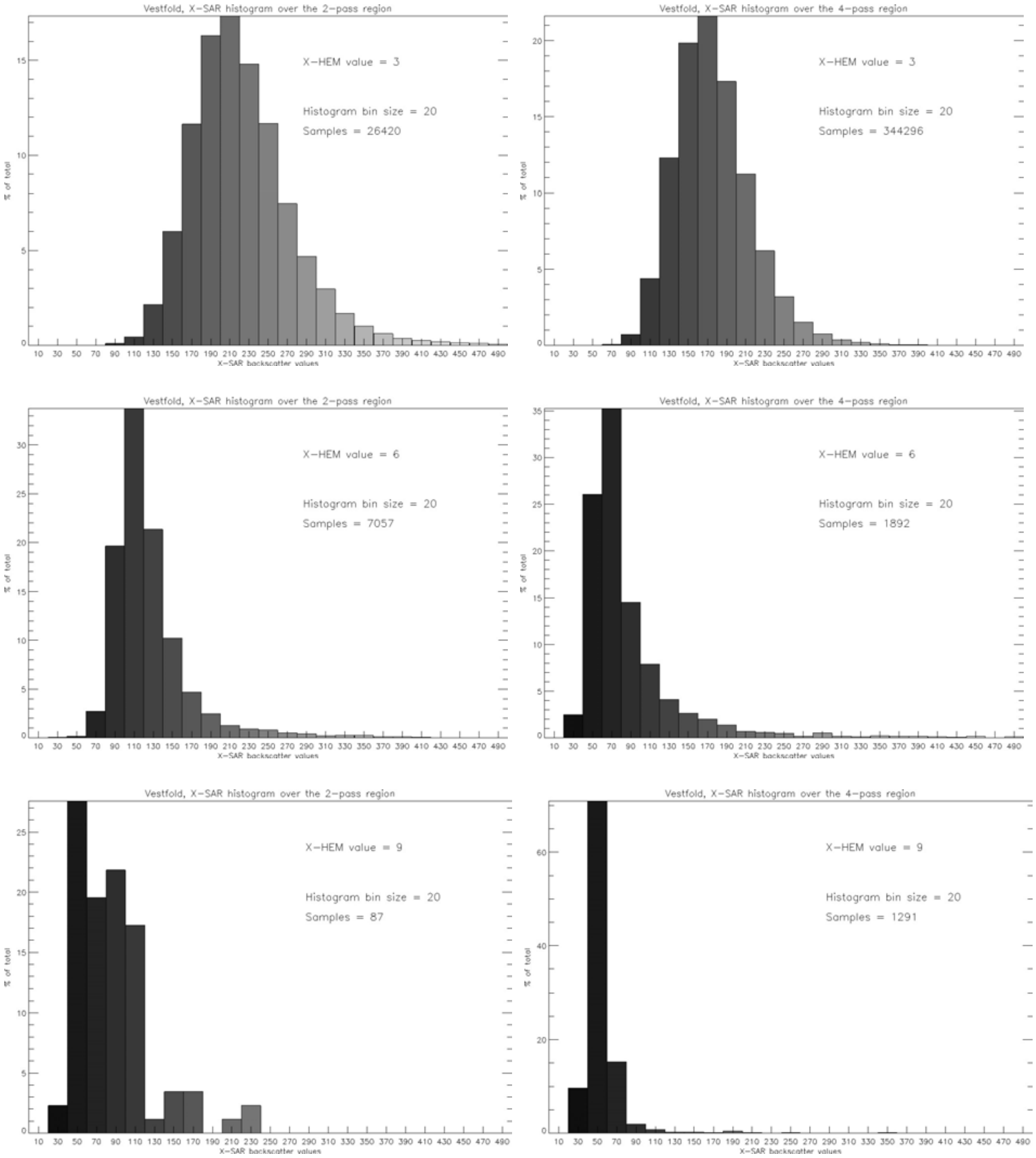


Figure 7.9 *SRTM X-band SAR image backscatter histograms for three different HEM settings over the 2-pass (left) and 4-pass (right) regions in Vestfold. Clearly, lower SAR backscatter gives rise to higher HEM values (and hence larger DEM uncertainties). More histograms are shown in Appendix A.5 and A.6.*

7.1.3 Conclusions

Results from analysis of the SRTM X-band data show that the majority of HEM values on land areas are 3 m or less with four acquired passes. Generally speaking, the height error increased by an additional 1-2 meters in regions with only two passes. We did not have available X-band data from a 1-pass region, but may deduce from the above observations that the majority of HEM values will be around 6-7 m in regions of only *one* SRTM acquisition.

HEM values of 3 m or higher seem to be independent of land cover type (e.g. forest or agriculture). However, small HEM values of 2 meters are most likely found at places with agricultural fields.

High HEM values (here: 7 m or larger) are often found in areas of:

- low SAR backscatter (e.g. water bodies or the runway at Sandefjord Airport Torp)
- InSAR decorrelation caused by layover or shadow effects

Land areas close to water boundaries may give HEM-values that are 1-2 m *higher* compared to the surroundings. This is probably due to the fact that the spatial low-pass filter mask (used in the interferometric processing) will distribute height uncertainties across boundaries with abrupt changes.

7.2 Evaluating the C-band DEM void data

The unedited SRTM C-band data do not have a separate HEM product file. Instead, particularly large errors are marked as *void data* by substituting a value of –32768 within the DEM data file itself. Now, by marking the *void data* with e.g. a red colour, the situation for the Vestfold test area corresponding to the SRTM C-band DEM is shown in Figure 7.11.

As we can see, only a small portion of the DEM will have *void data* in the Vestfold terrain. The void data are mainly corresponding to areas of particularly low SAR backscatter (lakes), but also radar beam shadow or layover regions.

It is interesting to investigate the SRTM X-band HEM values at the positions of the C-band *void data*. This analysis takes into account that the X-band data have “30 m” spatial resolution, while the C-band DEM is “90 m”. Results are shown as histograms in Figure 7.10. Clearly, most C-band *void data* samples are found over water bodies (left histogram), and only very few of the C-band pixels are located in areas with HEM values less than 7 m.

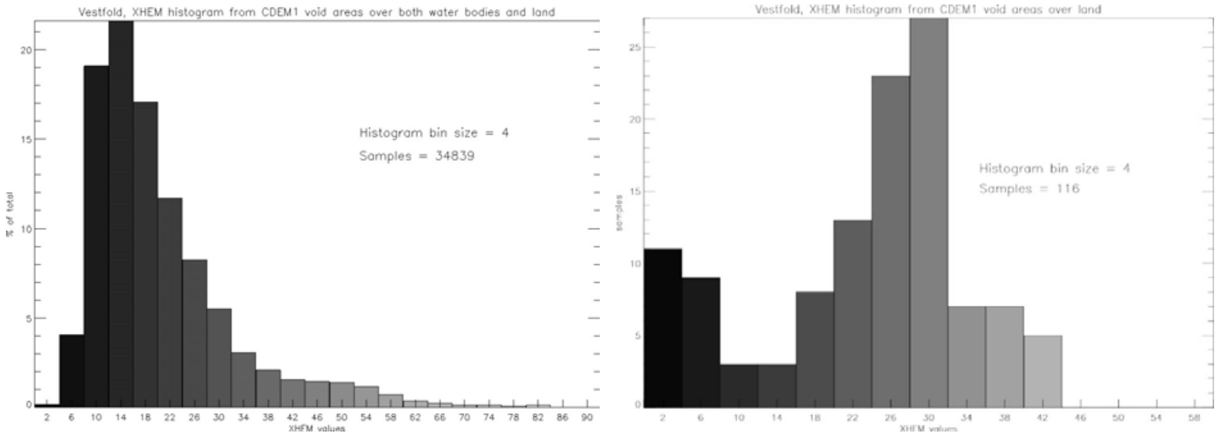


Figure 7.10 SRTM X-band HEM values in areas of SRTM C-band DEM void data. Vestfold test area, Norway.

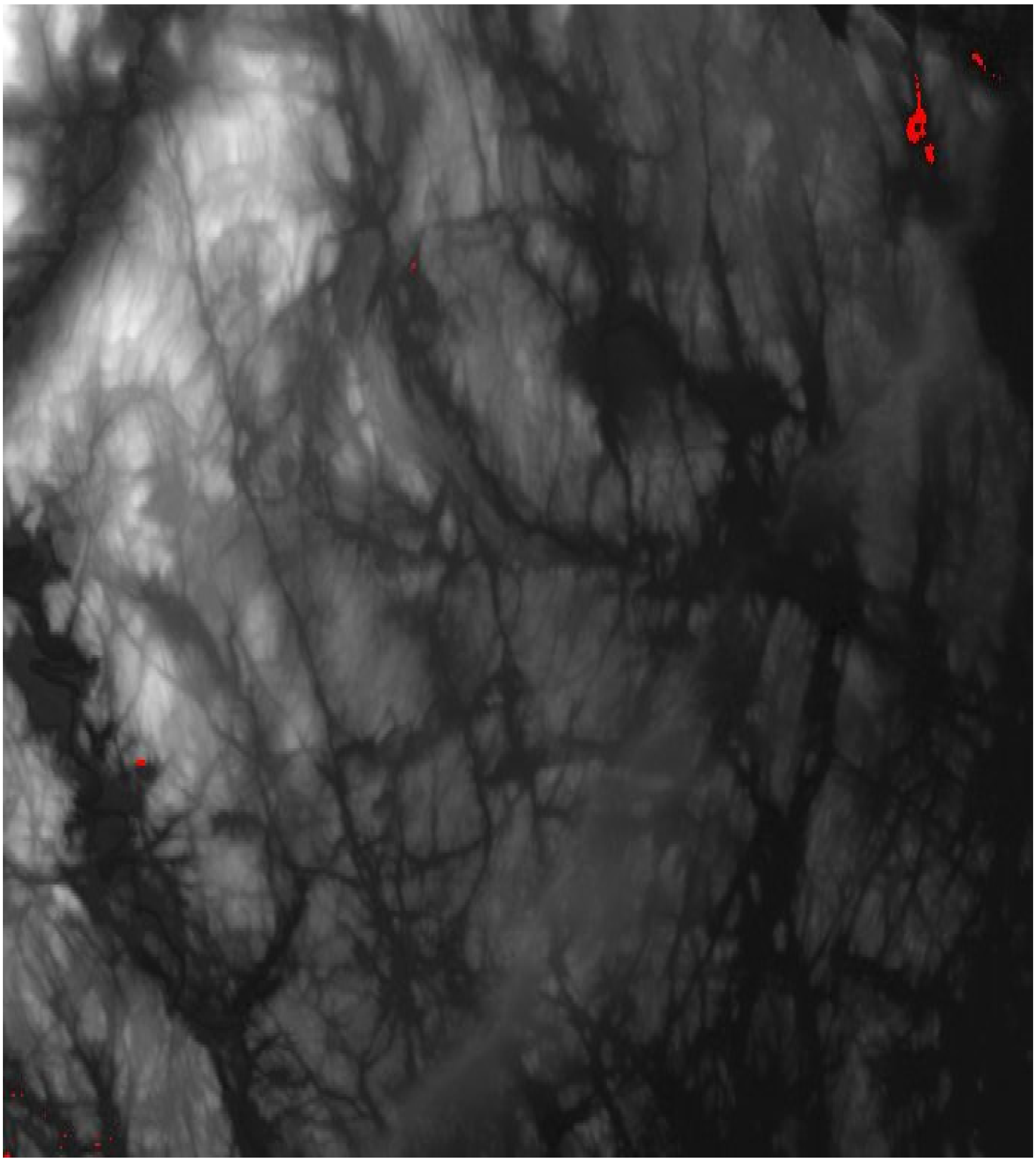


Figure 7.11 SRTM C-band DEM from Vestfold test area. Void data caused by e.g. very low backscatter from open water, shadowing and phase unwrapping anomalies are flagged with the value -32768, and are here marked with red colour. (© NASA/JPL 2004).

7.3 Absolute horizontal accuracy

The absolute horizontal accuracies of the SRTM DEMs are estimated by comparing the original SRTM DEMs with the N5 reference map. The test is performed over large parts of the Vestfold test area with elevations ranging from sea level to 420 m above sea level.

We will avoid resampling the SRTM DEMs as this may introduce errors and artefacts. The N5 raster map is therefore resampled twice to the geographic (Lat/Lon) coordinate system using a spatial sampling of 0.0002777 degrees and 0.0008333 degrees. These two spatial resolutions will fit with the original sampling of the SRTM X- and C-band DEM respectively.

Spatial cross-correlation is then performed at 80 positions (samples) within the data sets using a 2-dimensional FFT. The FFT has a block size of 128x128 pixels for the “30 m” X-band DEM and 64x64 pixels for the “90 m” C-band DEM.

By comparing the cross-correlation results in Table 7.2 with the specifications given in Table 2.1, it is clear that the absolute horizontal accuracies are inside the specifications for both the “30 m” X-band DEM and the “90 m” C-band DEM data. In fact, the horizontal accuracy for the X-band DEM must be said to be extremely good with a mean difference value $\mu < 2$ m, and $3\sigma < 5$ m !

Statistics of 80 samples	**X-band DEM (“30 m”)**		**Unedited C-band DEM (“90 m”)**	
	Northing (Lat.)	**Easting (Long.)**	**Northing (Lat.)**	**Easting (Long.)**
Pixel spacing [m]	30.9	15.8	92.8	47.4
RMSE [m]	2.2	1.1	14.3	8.9
Mean diff. μ [m]	1.7	-0.1	-12.3	7.9
St.Dev. σ [m]	1.4	1.1	7.5	4.0
Samples within specifications [%]	100	100	100	100

Table 7.2 Absolute horizontal accuracies for the “30 m” and “90 m” SRTM DEMs. The results are obtained by 2-dimensional cross-correlation of the N5 reference data set with the X-band and C-band DEMs respectively.

7.4 Vertical bias in the SRTM DEMs

The SRTM DEM data will normally be corrected for any vertical bias during the interferometric SAR processing procedures. However, it is worth investigating if there is any bias left, and how large these offsets may be. The vertical bias can be investigated in three ways:

1. Averaging SRTM DEM values over sea areas should give a value close to zero.
2. Comparing SRTM DEM values with GPS elevation measurements at fixed geographic locations on land.
3. Comparing the SRTM DEM values over flat open landscape with digital reference maps.

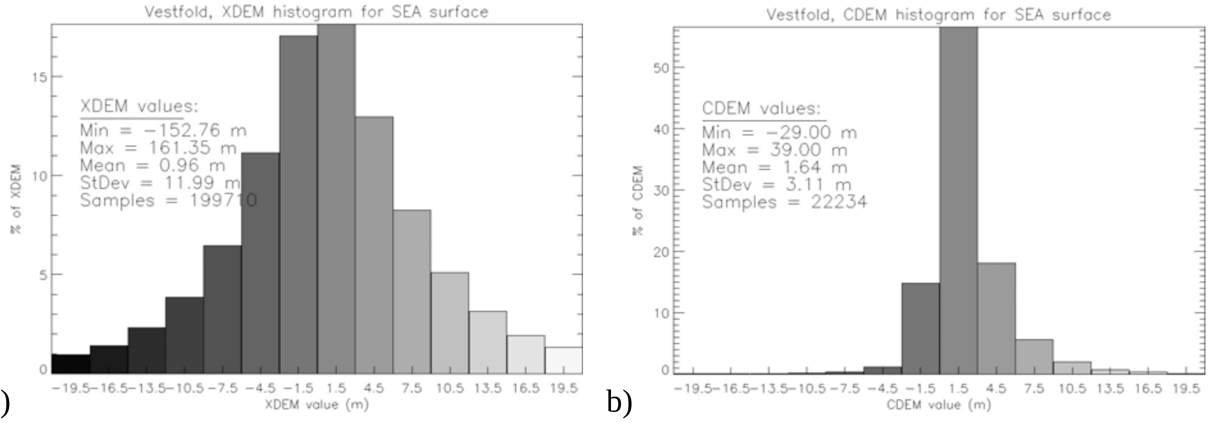
Results from these tests are given in the next three sections.

7.4.1 SRTM DEM values over the sea surface

The X-band DEM data will have elevation values set over the sea surface. The same is the case for the present “90 m” *unedited* C-band DEM. On the contrary, the *edited* “90 m” C-band DEM (Finalized by The National Geospatial-Intelligence Agency (NGA) in USA in 2004) will have all sea surfaces fixed to a value of zero. The sea surface will in this case be extracted from external databases or maps, and not the SRTM data itself.

SRTM DEM histograms from the Oslofjorden sea surface outside Vestfold County are shown in Figure 7.12. The unedited C-band DEM contains both elevation values and void values across the sea surface. The *void data* over the sea surface are very few, and are excluded from the statistics shown in Figure 7.12b). The X-band DEM shows a larger spread of elevation values from the sea surface than the C-band DEM. The reason for this is probably the different SAR frequencies and SAR processing schemes.

One major point to notice from the results shown in Figure 7.12 is that the *mean* value is very close to zero indeed. It is +0.96 m for the X-band DEM and +1.64 m for the C-band DEM. In



a) b)

Figure 7.12 SRTM DEM histograms obtained from the sea surface outside Vestfold County. a) The “30 m” X-band data. b) The “90 m” C-band data.

other words, analysing the SRTM DEMs over the sea surface indicates a very small vertical bias, - less than 2 meters on average. As a first result, this shows that the SRTM data seems to be very well adjusted for any vertical bias during the interferometric SAR processing. In order to confirm this result, the SRTM DEM values were subsequently compared to GPS measurements (section 7.4.2) and high-resolution digital reference maps (section 7.4.3).

7.4.2 Comparing SRTM DEM values with GPS measurements

Ten corner reflectors were deployed in Vestfold during the SRTM acquisitions. They were located at different elevation heights, and preferably in an open terrain near to agricultural fields or lakes. Norwegian Mapping Authority in Vestfold County ("Fylkeskartkontoret i Vestfold") did differential GPS (DGPS) measurements of the corner reflector positions in March 2000 using a Trimble GeoExplorer II instrument [Olaisen 2000]. The measured values are given in coloumns 2, 3 and 4 of Table 7.3. The DGPS measurements are estimated to be better than 0.5 m (one standard deviation) in the horizontal direction, and being better than 0.4 m (one standard deviation) in the vertical direction.

Using the numbers from Table 7.3, it is possible to estimate the overall accuracy of the four different elevation models by using the DGPS measurements as a reference. The result is given in Table 7.4, where there seems to be a small, but general vertical offset of -2.7 m for the X-band DEM and +1.5 m for the C-band DEM.

Place	**Differential GPS measurements at corner reflector positions**			**Digital elevation products, Height above geoid [m]**			
	WGS84, UTM 32		**Geoid height [m]**				
	Northing [m]	**Easting [m]**		**N5 DEM**	**N50 DEM**	**SRTM X-band DEM**	**SRTM C-band DEM**
Kvelde	6563910.4	551707.1	122.2	119.0	124.0	119.4	124
Stormyra	6570494.9	563912.3	142.1	143.4	144.5	141.1	145
Ramnes	6578769.3	571956.6	20.0	20.4	20.3	18.1	22
Rismyr	6564858.7	565562.9	93.8	93.3	92.7	89.9	94
Solbergvatn	6577773.7	556927.6	234.7	238.0	232.2	232.5	236
Torp A	6562879.5	572601.6	86.3	86.2	86.0	80.7	87
Torp B	6562735.0	572461.2	84.7	84.6	85.9	79.1	86
Åsvatn A	6573276.1	556364.2	275.9	277.0	280.9	273.8	277
Åsvatn B	6573332.7	556415.0	275.6	277.0	277.6	272.1	278
Jarlsberg	6573105.3	578754.4	10.9	NA	12.1	12.7	12

Table 7.3 Ground elevation heights at radar corner reflector positions for different products. The corner reflectors are all located in Vestfold County, Norway.

From Table 7.4, it is worth noting that the SRTM C-band DEM has a *lower* standard deviation than the N50 DEM, although the vertical offset with respect to the GPS measurements are slightly larger (+1.5 m as compared to +1.0 m). The low standard deviation is an indication that the C-band DEM may be closer to the truth over open landscape (non-forest areas) than the N50 DEM. This is investigated in more depth in section 8.1.

Elevation Model	**Vertical elevation offset with respect to 10 DGPS measurements**		
	Mean [m]	**St.Dev. [m]**	**RMSE [m]**
N5	0.4	1.7	1.6
N50	1.0	2.1	2.2
SRTM X-band DEM	-2.7	2.2	3.4
SRTM C-band DEM	1.5	0.8	1.7

Table 7.4 Four elevation models are evaluated at ten corner reflector positions in Vestfold, Norway. The vertical elevation offsets are referring to differential GPS measurements.

This small data set of only 10 DGPS measurements may not be all that reliable. In order to get more sample points, many elevation heights covering agricultural areas in Vestfold were evaluated. See results in the next section.

7.4.3 Comparing SRTM DEM values with N5 DEM

Differential GPS measurements were carried out for only 10 corner reflector positions (see previous section above). This is a fairly small data set when estimating the vertical bias. A much larger number of SRTM DEM values were therefore compared to a high-resolution digital elevation map. The test was performed over agricultural fields to avoid any natural SRTM DEM offsets caused by scattering from the vegetation volume (e.g. forest stands). The reference elevation map in this context is the N5 DEM.

The N5 DEM was first subtracted from the SRTM X-band DEM over the 2-pass and 4-pass regions in Vestfold. This will give a difference map, or error map:

$$ErrorMap_{SRTM} = DEM_{SRTM} - DEM_{Reference} \tag{7.1}$$

The two difference histograms are shown in Figure 7.13. The difference between the 2-pass and 4-pass regions is less than 0.5 m when comparing the *Mean* and *RMSE* values. We may assume that data taken from the 4-pass region are the most accurate ones. The result from agricultural fields in the 4-pass region in Vestfold shows that the original SRTM X-band DEM values are 1.02 m lower than the ‘truth’.

The same procedure was carried out for the unedited “90 m” SRTM C-band DEM. However, now *all* agricultural fields as marked in Figure 6.4 were used (and not only fields from the X-band 4-pass region). The difference histogram is shown in Figure 7.14. The original C-band DEM values are 3.32 m higher than the ‘truth’ (i.e. a vertical bias of +3.32 m is found with respect to the N5 reference DEM).

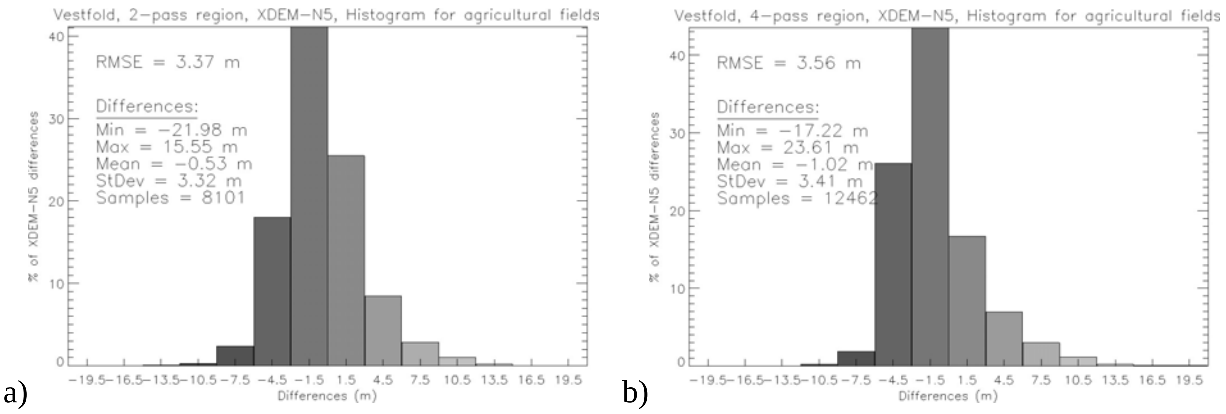


Figure 7.13 Histograms of elevation differences between the N5 DEM and the X-band DEM over agricultural fields in Vestfold. a) Data from the 2-pass region. b) Data from the 4-pass region. The DEM grid spacing is ca. 30x15 m.

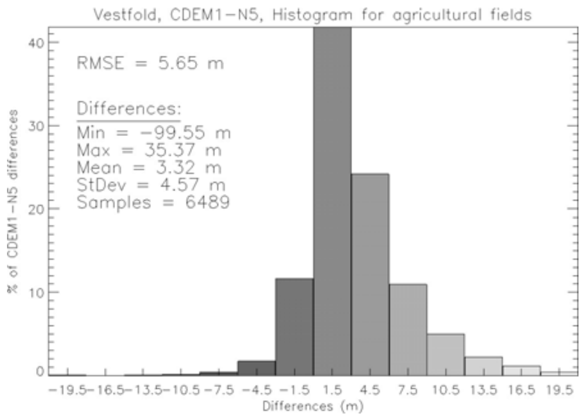


Figure 7.14 Histogram of elevation differences between the N5 DEM and the C-band DEM over agricultural fields in Vestfold. The DEM grid spacing is ca. 90x45 m.

7.4.4 Assessment of the estimated vertical bias

The previous three sections show that there is a small vertical bias in the SRTM X-band DEM and C-band DEM over the Vestfold test area in Norway. The results are summarised in Table 7.5, which also includes the bias difference between the two SRTM DEM products.

Table 7.5 shows that the absolute vertical bias is less than +/- 3.3 m for all methods.
The first method used the sea surface to estimate the vertical bias. This method gave a one standard deviation of as much as 12 m for the X-band DEM product (see Figure 7.12a). The other methods gave a one standard deviation from 0.8 m to 4.6 m. The sea surface method is therefore excluded from further analysis.

The second method used differential GPS positions. Although only 10 sample points were used, this gave a good indication of the absolute vertical offset of the two SRTM products: The X-band DEM should be adjusted up by 2.7 m and the C-band DEM adjusted down by 1.5 m in order to match the true ground elevations.

Estimation method	**Estimated absolute SRTM vertical bias in Vestfold [m]**		**Bias difference between X-band and C-band DEM [m]**
	X-band DEM	**C-band DEM**	
1. Sea surface	+0.96	+1.64	0.7
2. GPS positions	-2.7	+1.5	4.2
3. N5 DEM at agricultural fields	-1.02	+3.32	4.3

Table 7.5 Summary of the vertical bias estimated for the SRTM DEM products covering Vestfold test area in Norway.

More than 6000 sample points were evaluated using the third method (see Figure 7.13 and Figure 7.14). This method referred to the N5 DEM data over agricultural fields rather than GPS measurements. The offset *difference* between the two SRTM products is almost the same as for the GPS measurements: 4.3 m as compared to 4.2 m for the GPS data. Similar offset differences (3.3 m and 2.9 m) were reported across two profiles that covered both agricultural and forested areas [Weydahl 2004].

Another effect noticed from Table 7.5 is that the absolute vertical offset is “lifted up” by approximately 1.7 m when using the N5 DEM rather than GPS measurements. This difference in result when using methods 2 and 3 can be explained by uncertainties when using only 10 GPS sample points, but also uncertainties in the N5 DEM when estimating the vertical offset over agricultural fields (the one standard deviations were from 3.3 m to 4.6 m). However, since the N5 DEM is considered as the reference data set for the SRTM analysis over Vestfold, it will be most sensible to also use this dataset when estimating the absolute vertical offset of the SRTM DEMs. As we shall see later, the vertical offset is used to correct the SRTM DEMs before carrying out detailed analysis over particular features of interest (see section 7.5 and 7.7).

We have seen that the SRTM absolute vertical bias is in the order of a few meters for the Vestfold test area. An interesting question is whether or not this small vertical bias will lead to errors that are larger than the product specifications given in Table 2.1: “absolute vertical error < 16 m with 90 % confidence”. The RMSE and number of samples within the 90 % confidence interval are estimated in order to answer this question. Results from three surface cover types are given in Table 7.6 to Table 7.8. Both the “30 m” X-band DEM (‘XDEM’) and the “90 m” C-band DEM (‘CDEM1’) will be within the specifications (numbers marked with green colour), except for C-band DEM data over dense forest stands (red colour).

Dense forest stands will give an elevation value that is modelled by the height of the forest. An *additional* vertical offset of +3.32 m will then change the +/- 16 m confidence level to 86 %. For all other surface cover types as much as 95 % to 99 % of the samples are within the +/- 16 m confidence boundary. RMSE values less than 5 m is also very good! It is worth noticing that the SRTM DEM products are within the specifications when considering all land surface cover types together (including the dense forest stands), see Table 7.8.

SRTM product (not height offset corrected)	**Agricultural fields, Vestfold**						
	RMSE (m)	Mean diff. (m)	St.Dev. (m)	Samples within +/- 16 m (%)	Samples within +/- 20 m (%)	Histogram boundary at 90 % samples (+/- m)	Histogram boundary at 95 % samples (+/- m)
XDEM, 2-pass	3.4	-0.53	3.3	99.9	99.9	**5.4**	6.7
XDEM, 4-pass	3.6	-1.02	3.4	99.8	99.9	**5.3**	6.6
CDEM1	5.7	3.32	4.6	98.6	99.6	**8.7**	11.3

Table 7.6 Statistics of SRTM DEM data when referring to the N5 topographic map. The SRTM DEMs are the original ones, and they are not corrected for height offsets. The XDEM is evaluated over all HEM values, the CDEM1 exclude void pixels.

SRTM product (not height offset corrected)	**Dense coniferous forest, Vestfold**						
	RMSE (m)	Mean diff. (m)	St.Dev. (m)	Samples within +/- 16 m (%)	Samples within +/- 20 m (%)	Histogram boundary at 90 % samples (+/- m)	Histogram boundary at 95 % samples (+/- m)
XDEM, 2-pass	8.7	7.13	5.0	97.1	99.5	**13.0**	14.7
XDEM, 4-pass	8.9	7.74	4.3	97.9	99.8	**13.2**	14.7
CDEM1	11.8	10.05	6.2	85.8	95.6	**17.2**	19.6

Table 7.7 Statistics of SRTM DEM data when referring to the N5 topographic map. The SRTM DEMs are the original ones, and they are not corrected for height offsets. The XDEM is evaluated over all HEM values, the CDEM1 exclude void pixels.

SRTM product (not height offset corrected)	**All land surface classes, Vestfold**						
	RMSE (m)	Mean diff. (m)	St.Dev. (m)	Samples within +/- 16 m (%)	Samples within +/- 20 m (%)	Histogram boundary at 90 % samples (+/- m)	Histogram boundary at 95 % samples (+/- m)
XDEM, 2-pass	5.5	2.16	5.0	99.4	99.8	**8.7**	10.9
XDEM, 4-pass	5.0	1.63	4.7	99.6	99.9	**8.3**	10.3
CDEM1	8.1	5.20	6.2	95.1	98.3	**13.2**	16.0

Table 7.8 Statistics of SRTM DEM data when referring to the N5 topographic map. The SRTM DEMs are the original ones, and they are not corrected for height offsets. The XDEM is evaluated over all HEM values, the CDEM1 exclude void pixels.

7.5 Absolute height accuracy of the SRTM DEMs

We have seen in chapter 7.4.4 that the SRTM DEM products covering the Vestfold test area had a small absolute vertical bias. This bias (offset) was estimated to –1.02 m and +3.32 m for the SRTM X-band and C-band DEMs respectively. We have also seen that, in general, the SRTM DEMs will be within the specifications even without correcting for these small vertical offsets. However, the SRTM C-band DEM will be slightly outside the specifications over dense forest stands if the vertical offset is not corrected for.

In this chapter, the SRTM DEMs are corrected for any absolute vertical bias *prior* to the absolute height accuracy evaluation:

- Corrected SRTM X-band DEM = Original SRTM X-band DEM + 1.02 m
- Corrected SRTM C-band DEM = Original SRTM C-band DEM - 3.32 m

The results are given in Figure 7.15 and Table 7.9 to Table 7.11. The difference histograms in Figure 7.15 (top) show a mean value of zero. This means that the vertical offset correction has worked very well (compare with histograms in Figure 7.13b and Figure 7.14).

The RMSE level is less than 4.6 m for agricultural fields, and more than 99 % of the samples are within the +/- 16 m boundary for this surface cover type. From these results, it is clear that the SRTM DEM data are far better than the specifications, especially over open non-forest areas!

Even over dense coniferous forest stands, the 90 % confidence level give a boundary of +/- 14 m (as compared to the +/- 16 m product specification). This boundary is even brought down to 9.2 m and 10.7 m for the X-band and C-band DEMs respectively when analysing *all* surface cover types together (which also include the dense forest stands). So, in general, more than 99 % and 97 % of the samples are within the +/- 16 m level boundary for the X-band and C-band DEMs respectively.

From the histograms in Figure 7.15, we can see that the maximum and minimum difference values can be quite small/large (-240 / +95) for the C-band DEM. However, investigating this in more detail showed that only 17 samples out of 221188 have a difference larger than +/- 50 m. The same numbers for the X-band DEM (evaluated all over Vestfold, and not only the 2-pass or 4-pass regions) are: minimum= -132, maximum=152, and 2492 samples out of 1991211 have a difference larger than +/- 50 m. Clearly, only a *minor* portion of the SRTM samples have DEM values that may be considered as outliers. It is interesting to notice from the histograms in Figure 7.15 that there is a small vertical offset between the mean values estimated over the dense forest stands: The X-band DEM is offset 8.76 m, while the C-band DEM is offset 6.73 m. This is a difference of around 2 m. Estimating the difference *directly* using the two SRTM DEMs, gave a value of 0.93 m (see Figure 7.16). In other words, the C-band SAR signal penetrates 1-2 meters deeper into the canopy, as compared to X-band SAR.

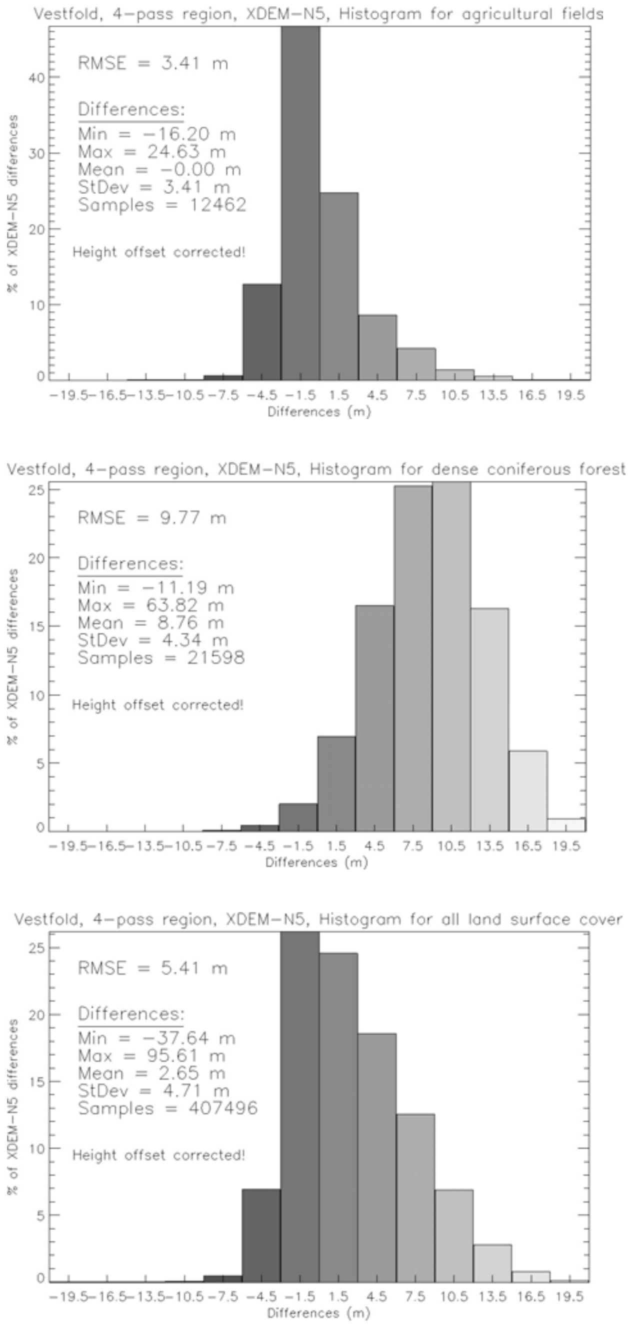


Figure 7.15 Difference histograms between N5 DEM and SRTM X-band DEM (left) and SRTM C-band DEM (right) respectively. The two SRTM DEMs were corrected for vertical bias <u>prior</u> to this calculation. The vertical bias is estimated by comparing the SRTM DEMs with N5 DEM over agricultural fields.

SRTM product (height offset corrected)	**Agricultural fields, Vestfold**						
	RMSE (m)	Mean diff. (m)	St.Dev. (m)	Samples within +/- 16 m (%)	Samples within +/- 20 m (%)	Histogram boundary at 90 % samples (+/- m)	Histogram boundary at 95 % samples (+/- m)
XDEM, 2-pass	3.4	0.49	3.3	99.9	99.9	**5.4**	7.0
XDEM, 4-pass	3.4	0.0	3.4	99.8	99.9	**5.2**	7.1
CDEM1	4.6	0.0	4.6	99.3	99.7	**6.5**	8.7

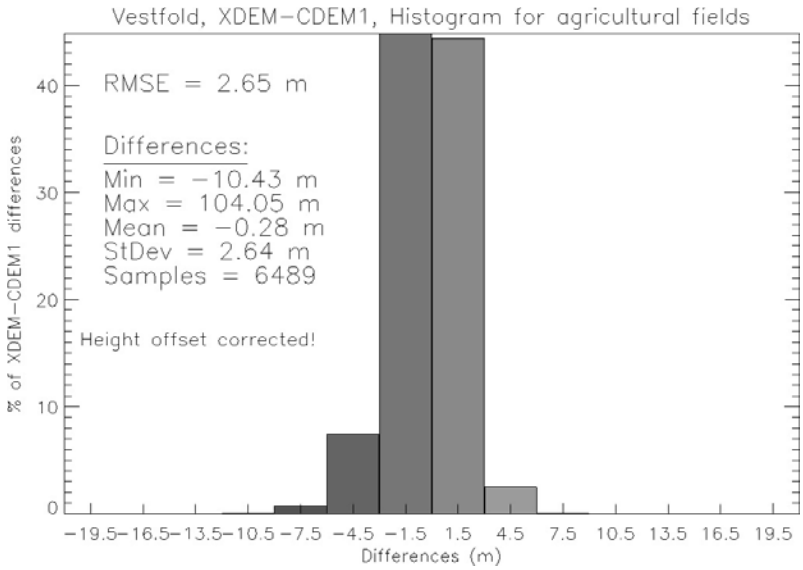
Table 7.9 *Statistics of SRTM DEM data when referring to the N5 topographic map. The SRTM DEMs were corrected for height offsets* prior *to the estimation. The XDEM is evaluated over all HEM values, the CDEM1 exclude void pixels.*

SRTM product (height offset corrected)	**Dense coniferous forest, Vestfold**						
	RMSE (m)	Mean diff. (m)	St.Dev. (m)	Samples within +/- 16 m (%)	Samples within +/- 20 m (%)	Histogram boundary at 90 % samples (+/- m)	Histogram boundary at 95 % samples (+/- m)
XDEM, 2-pass	9.6	8.15	5.0	95.7	99.2	**14.0**	15.7
XDEM, 4-pass	9.8	8.76	4.3	95.9	99.8	**14.2**	15.7
CDEM1	9.1	6.7	6.2	94.5	98.3	**14.0**	16.5

Table 7.10 *Statistics of SRTM DEM data when referring to the N5 topographic map. The SRTM DEMs were corrected for height offsets* prior *to the estimation. The XDEM is evaluated over all HEM values, the CDEM1 exclude void pixels.*

SRTM product (height offset corrected)	**All land surface classes, Vestfold**						
	RMSE (m)	Mean diff. (m)	St.Dev. (m)	Samples within +/- 16 m (%)	Samples within +/- 20 m (%)	Histogram boundary at 90 % samples (+/- m)	Histogram boundary at 95 % samples (+/- m)
XDEM, 2-pass	5.9	3.18	5.0	99.1	99.8	**9.7**	12.0
XDEM, 4-pass	5.4	2.65	4.7	99.4	99.9	**9.2**	11.5
CDEM1	6.5	1.88	6.2	97.5	99.1	**10.7**	13.2

Table 7.11 *Statistics of SRTM DEM data when referring to the N5 topographic map. The SRTM DEMs were corrected for height offsets* prior *to the estimation. The XDEM is evaluated over all HEM values, the CDEM1 exclude void pixels.*



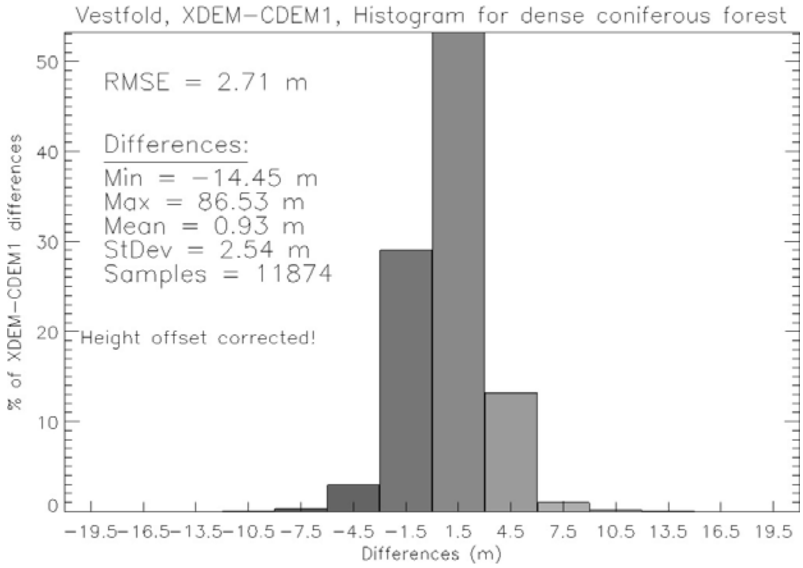


Figure 7.16 SRTM DEM difference histograms over agricultural fields (top) and dense coniferous forest stands (bottom).

7.6 Relative height accuracy of the SRTM DEMs

Relative height accuracy of a DEM can be performed in different ways. The SRTM project definitions for the relative vertical accuracy stem from the C-band swath width and require that the height errors have an arbitrary mean and a variation of 6 m (90 %) within a 225 x 225 km area. The SRTM height errors can then be analysed over long ocean data takes using very accurate ocean height models [Rabus *et al.* 2003]. The specifications of the relative height accuracy for the SRTM X-band and C-band DEM data are < 6 m and < 10 m respectively at 90 % confidence level. This was achieved using an ocean model [Rabus *et al.* 2003].

The test areas in Norway do not extend over so large areas, and are located on land. The relative height accuracy test is therefore performed over different surface cover types using the principle described in chapter 5.3. Results are shown in Table 7.12 and Table 7.13. Adjacent sample points are selected to the east (e+1,n) and to the north (e,n+1) of an initial position (e,n). Adjacent diagonal points are also investigated (e+1,n+1).

The result shows that the relative height accuracy is within the specifications for all adjacent sample points, regardless of direction. The lowest RMSE is obtained from the agricultural surface cover type where RMSE=1.48 m and 2.83 m for X-band and C-band respectively. The situation with one sample point in-between the adjacent points (i.e. e+2 and/or n+2) is also investigated, and the results then slightly exceed the specifications.

The right coloumn in Table 7.12 and Table 7.13 shows the 90 % confidence level when multiplying the RMSE-value in coloumn three with the factor 1.649. This simple multiplication to estimate the confidence level assumes that the relative height differences are Gaussian distributed (see chapter 5.2). Another way of using this multiplying factor of 1.649 is that we can set the upper limit for the RMSE-values we estimate in the test:

- X-band DEM with 90 % confidence < 6 m => estimated RMSE should be < 3.64 m
- C-band DEM with 90 % confidence < 10 m => estimated RMSE should be < 6.06 m

Surface cover type	**Adjacent points (easting, northing)**	**Estimated RMSE [m]**	**Confidence**	**90% confidence using RMSE*1.649**
Agriculture	(e,n) & (e+1,n)	1.48	± 3 m gives 95% conf.	2.44 m
	(e,n) & (e,n+1)	2.15	± 4 m gives 93% conf.	3.55 m
	(e,n) & (e+1,n+1)	2.37	± 4 m gives 91% conf.	3.91 m
Forest	(e,n) & (e+1,n)	2.20	± 4 m gives 94% conf.	3.63 m
	(e,n) & (e,n+1)	3.00	± 5 m gives 92% conf.	4.95 m
	(e,n) & (e+1,n+1)	3.45	± 6 m gives 93% conf.	5.69 m
All land classes	(e,n) & (e+1,n)	2.17	± 4 m gives 95% conf.	3.58 m
	(e,n) & (e,n+1)	2.81	± 5 m gives 93% conf.	4.63 m
	(e,n) & (e+1,n+1)	3.21	± 5 m gives 90% conf.	5.29 m

Table 7.12 Relative vertical error for SRTM X-band DEM over Vestfold. Height offset (bias) in the SRTM DEM is corrected prior to the RMSE estimation. Specifications of the 90 % confidence level is set to < 6 m.

Surface cover type	**Adjacent points (easting, northing)**	**Estimated RMSE [m]**	**Confidence**	**90% confidence using RMSE*1.649**
Agriculture	(e,n) & (e+1,n)	2.83	± 5 m gives 92% conf.	4.67 m
	(e,n) & (e,n+1)	3.04	± 5 m gives 92% conf.	5.01 m
	(e,n) & (e+1,n+1)	3.24	± 5 m gives 90% conf.	5.34 m
Forest	(e,n) & (e+1,n)	4.78	± 8 m gives 91% conf.	7.88 m
	(e,n) & (e,n+1)	5.06	± 8 m gives 90% conf.	8.34 m
	(e,n) & (e+1,n+1)	5.19	± 9 m gives 91% conf.	8.56 m
All land classes	(e,n) & (e+1,n)	5.19	± 9 m gives 92% conf.	8.56 m
	(e,n) & (e,n+1)	5.93	± 9 m gives 90% conf.	9.78 m
	(e,n) & (e+1,n+1)	5.97	± 10 m gives 92% conf.	9.85 m

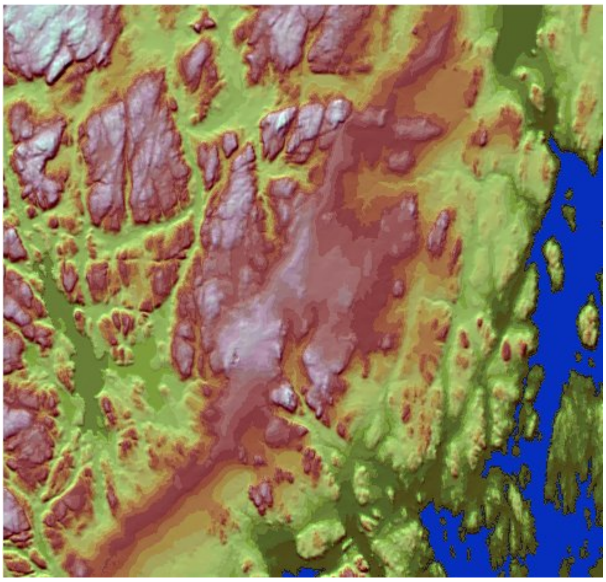
Table 7.13 Relative vertical error for SRTM C-band DEM over Vestfold. Height offset (bias) in the SRTM DEM is corrected prior to the RMSE estimation. Specifications of the 90 % confidence level is set to < 10 m.

7.7 Analysis of particular features

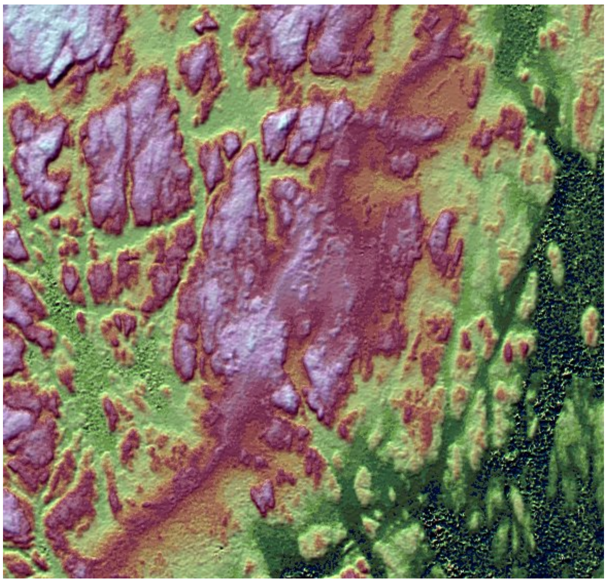
7.7.1 A visual inspection of the SRTM DEMs

First, a general visual comparison of the SRTM DEMs is carried out with respect to the N5 reference DEM. An example from Vestfold County is shown in Figure 7.17. The DEM colours are here coded according to a USGS colour look-up-table, and using a colour elevation interval of 6 m. Clearly, many details are present in the SRTM DEMs. Yes, even elevation details that are not seen in the N5 reference DEM! Several of these features will be studied in more detail in the next sections of this report.

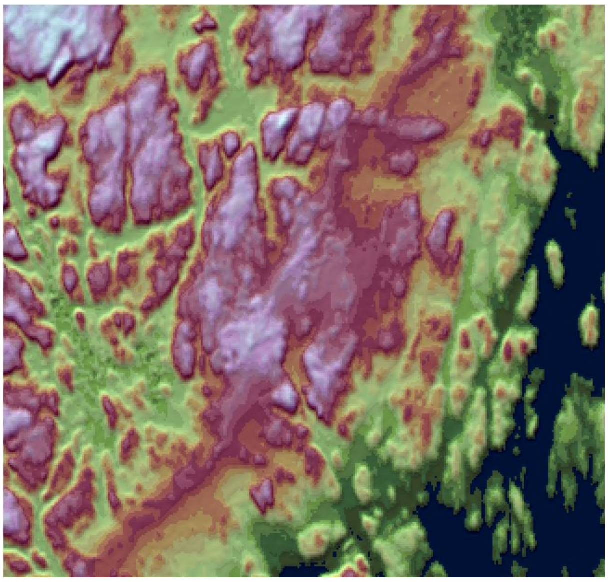
Optical IRS-1 C satellite image (© Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997).



Reference DEM based on 1:5000 (N5) vector elevation contours obtained from Norwegian Mapping Authority.



SRTM X-band DEM, 30 m data (© DLR 2003).



SRTM C-band DEM, 90 m unedited data (© NASA/JPL 2004).

Figure 7.17 Parts of Vestfold County, Norway. The three DEMs are using a colour elevation interval of 6 m.

7.7.2 Water bodies

Several of the lakes were frozen at the time of SRTM data acquisition in February 2000. The SRTM DEMs analysed here gave errors over lake surfaces in the range from 2 meters to more than 90 meters. The large spread of values is clearly shown in the X-band DEM histogram plots for sea and lake surfaces in Figure 7.8.

Lakes, rivers and sea surfaces are clearly prone to large errors in the SRTM system! These surface types often result in a low SAR backscatter for the SRTM system (see example in the SRTM X-band SAR image shown in Figure 7.6). This low SAR backscatter gives a low S/N ratio, which in turn leads to larger phase errors in the SAR data. These phase errors translate into larger interferometric height errors. This is clearly seen when comparing the SRTM X-band SAR image in Figure 7.6 with the corresponding Height Error Map (HEM) shown in Figure 7.6.

Due to these effects, we recommend to mask out lakes and water surfaces from the SRTM DEM. This may be done by means of other information sources like the SRTM SAR images, Landsat TM images or thematic maps.

7.7.3 Agricultural fields

As already shown in Figure 7.15 and Table 7.9, the SRTM system will give high quality DEMs over agricultural fields. An RMSE of 3.4 m and 4.6 m was estimated for the X-band and C-band DEMs respectively. This corresponds to a 90 % confidence level of 5.4 m and 6.5 m respectively. This is indeed well within the SRTM specifications of 16 m.

By comparing the SRTM X-band SAR image in Figure 7.6 with the corresponding Height Error Map (HEM) in Figure 7.6, it is clear that the smallest height errors are found in the agricultural fields having the strongest SAR backscatter.

The SRTM DEMs capture small elevation changes within an agricultural landscape much better than the N50 reference DEM. One of the reasons for this is that the N50 DEM is based on vector data having elevation contour intervals of 20 m. Small rivers and streams that cut through an agricultural region may not be captured in the N50 DEM. Such features are much better represented in the SRTM DEMs!

7.7.4 Forest areas

The SRTM used C-band and X-band SAR systems with wavelengths of 6 cm and 3 cm respectively. At these wavelengths, the backscattered SAR signal from a forest stand may originate from the canopy layer (see illustration in Figure 2.8). Now, depending on the density of the forest stand, most of the backscattered SAR signal will either originate from the crown, the branches, or the ground. In Vestfold, there are many forest stands consisting of only coniferous forest, only deciduous forest, or a mix of these two. The age, tree height and density of the forest stands will vary.

Two dense deciduous forest stands at Jarlsberg Manor can be used as an introductory example. An aerial photo from Jarlsberg is shown in Figure 7.18. The SRTM X-band and C-band DEM profiles across this area are plotted in Figure 7.19. The two forest stands (A and B) are located on top of two small hills that reach up to around 19 m and 26 m above sea level respectively. However, the SRTM elevations reach up to 33 m (profile from area A) and 27 m (profile from area B) when referring to Figure 7.19. It is clear that the SRTM SAR system measures the reflective surface height and that the canopy in these dense forest stands add several meters to the ground level (see chapter 2.5). These forest stands were analysed in more detail using the N50 DEM as reference [Sagstuen 2003].

Figure 7.18 Aerial photo from parts of Jarlsberg Manor showing two old dense deciduous forest areas. Photo taken in August 1999. © FFI 1999.

The two SRTM DEM profiles from Jarlsberg Manor (Figure 7.19) also show a small local vertical difference of 1.2 m across the agricultural region. This is even after performing the general vertical offset correction over Vestfold (see estimated vertical offset values in chapter 7.5). The SRTM difference increased to 2.7 m over the dense forest stand. This means that there is a *slight* difference in penetration depth of the two SAR systems (only 1.5 m when adjusting the vertical difference to the local agricultural profile). From this we will conclude that the C-band SAR system penetrates 1-2 m deeper into the canopy layer as compared to the X-band system.

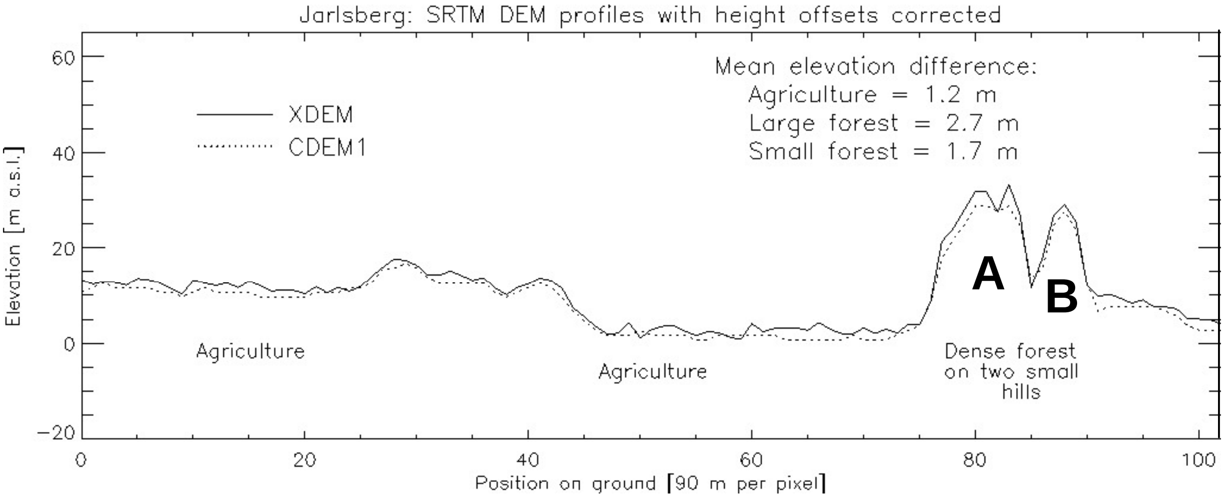


Figure 7.19 SRTM elevation profiles (from West to East) crossing over the two dense forest stands at Jarlsberg Manor, Vestfold County. See photo in Figure 7.18.

The SRTM elevations may be represented as an SRTM *error map* (see equation *(7.1))*. Alternatively, we may call this a *difference image* with respect to the high-resolution digital reference DEM:

$$DifferenceImage_{SRTM} = DEM_{SRTM} - DEM_{Reference} \tag{7.2}$$

A result of this DEM subtraction is shown in Figure 7.20 where an SRTM *difference image* (right) is displayed together with a multispectral optical satellite image (left). The difference image represents SRTM X-band DEM errors in the range from –30 m to +20 m with respect to the true ground elevations found in the reference map. Clearly, the higher SRTM elevations (white tone) are corresponding to coniferous forest stands (dark green) or deciduous forest stands (yellow) as seen in the optical satellite image on the left side of Figure 7.20.

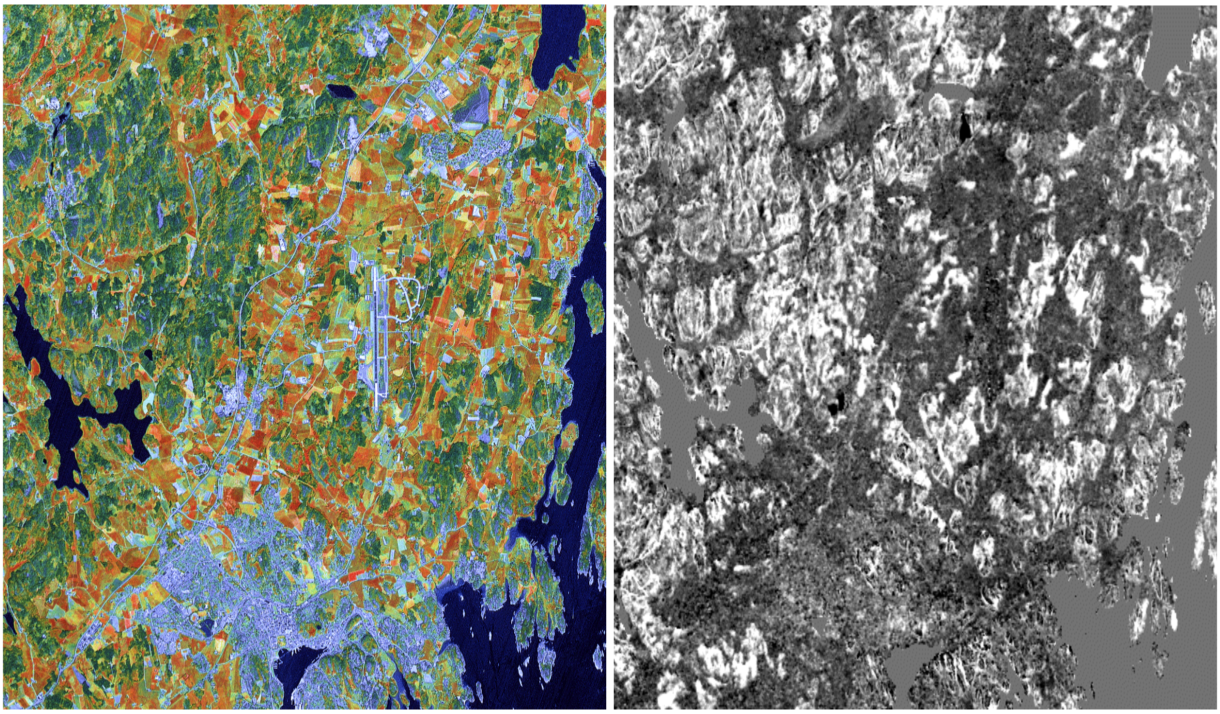


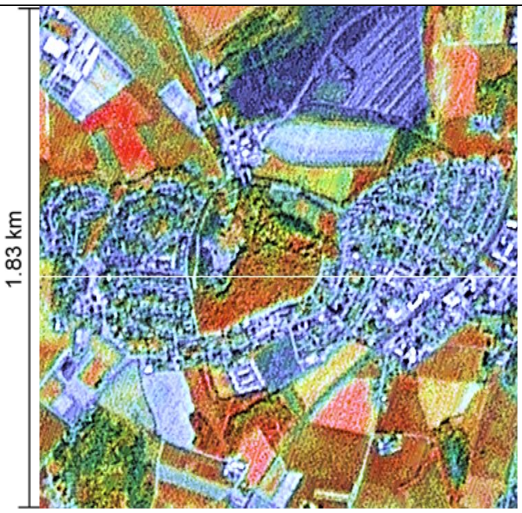
Figure 7.20 Forest and agricultural areas in Vestfold, Norway.

Left: *A multispectral IRS-1C optical satellite image showing the coniferous forest stands as dark green areas. Deciduous forest stands (as well as some agricultural fields) will show up in a dark orange colour. (IRS-1C image: © Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997.)*

Right: *An SRTM difference image (X-band DEM – N5 DEM) showing forest stands with white tone (up to +20 m elevation difference), most agricultural fields as grey tone (around 0 m elevation difference) and black colour in areas where the X-band DEM has a value much lower (e.g. –30 m) than the reference DEM.*

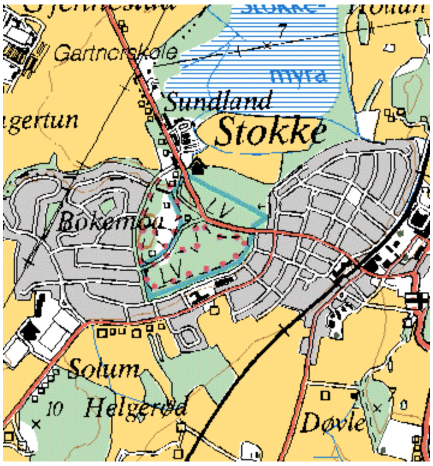
A more thorough investigation was carried out over several forest areas in Vestfold. No *in-situ* data with measured forest height and density was available for this study. More details of the forest stand parameters would clearly be of interest for another study in the future. The investigations performed here are restricted to the present material (SRTM, digital maps, satellite images, aerial photos) by evaluating elevation differences found in images and 2D-plots. Results from the selected, relatively dense, forest stands are shown in Figure 7.21 to Figure 7.26.

In general, the results indicate that dense, old coniferous forest in Norway will be mapped with an elevation 15-17 m above the ground. This is an error of 6-8 m if we assume that a dense coniferous forest in Vestfold will have an average tree height of 23 m. These results are similar to what was obtained by Kellndorfer [Kellndorfer *et al.* 2004a, Kellndorfer *et al.* 2004b] who found that SRTM C-band DEM data underestimated the elevation of the investigated forest types in North America by approximately 6 m.

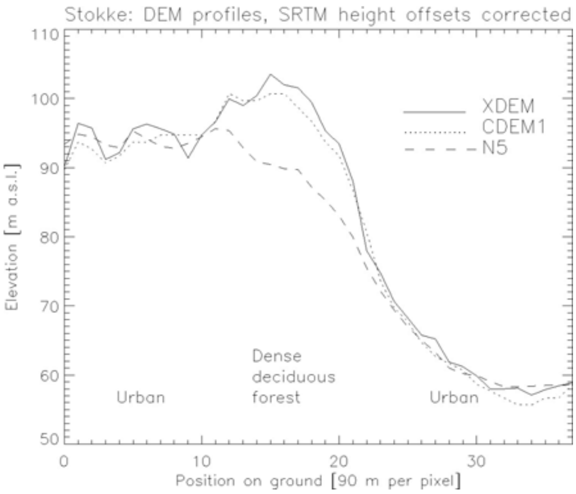


IRS-1C satellite image.

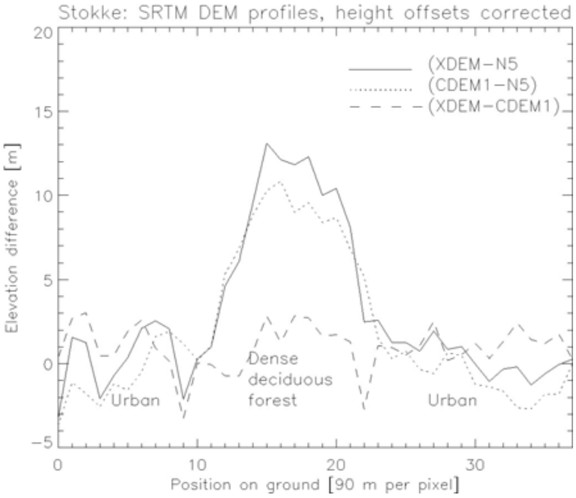
© Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997

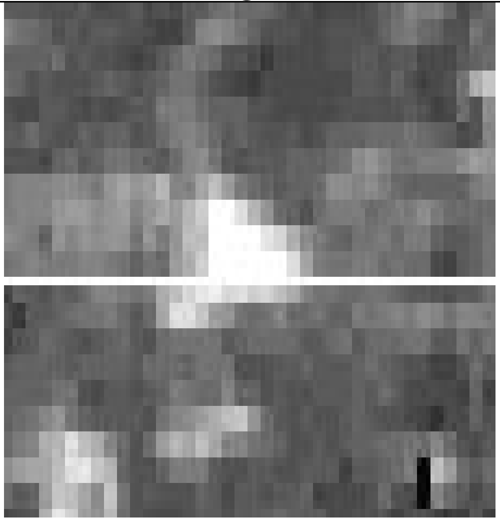


M711 (1:50 000) topographic map in WGS84 UTM32. Updated 1990. © Statens Kartverk. Center position: 5 73 660E, 65 65 650N



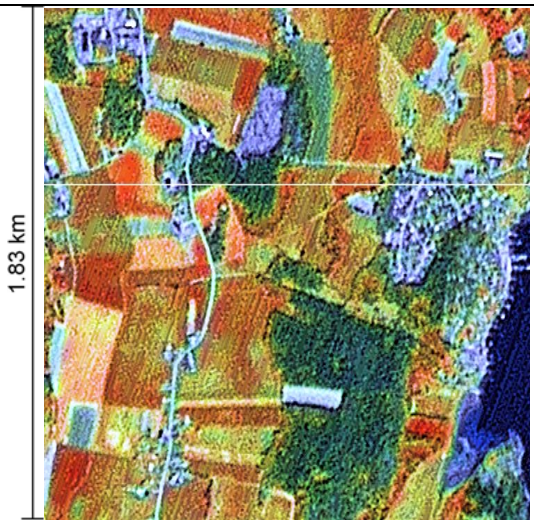
DifferenceImage = XDEM-N5



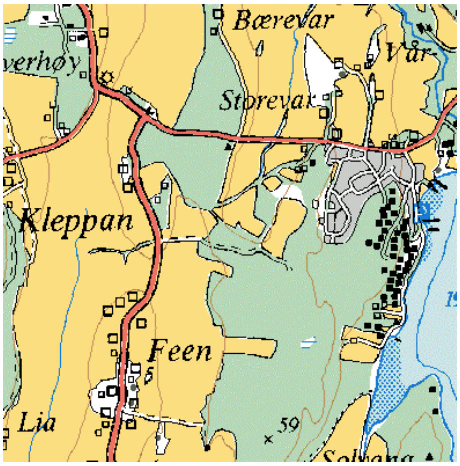


DifferenceImage = CDEM1-N5

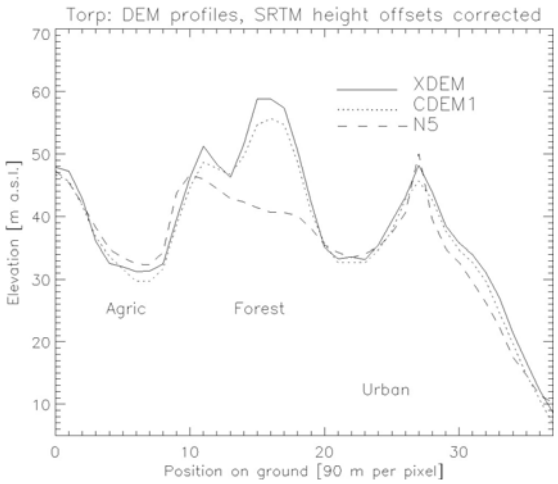
Figure 7.21 A nature conservation area in the middle of Stokke town in Vestfold. The area consists of a tall and dense deciduous forest. The white horizontal lines in the images show the location of the profiles drawn in the two plots. Average DEM difference between the two SRTM systems over the central forest area is 1.88 m.

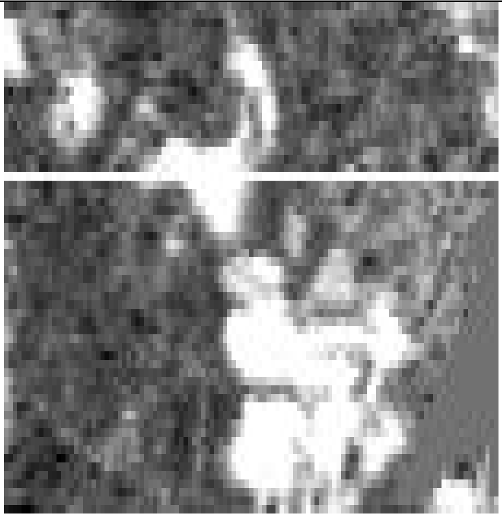


IRS-1C satellite image.

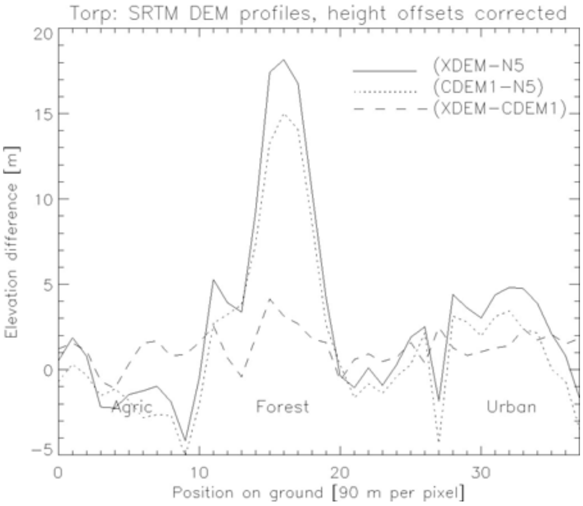


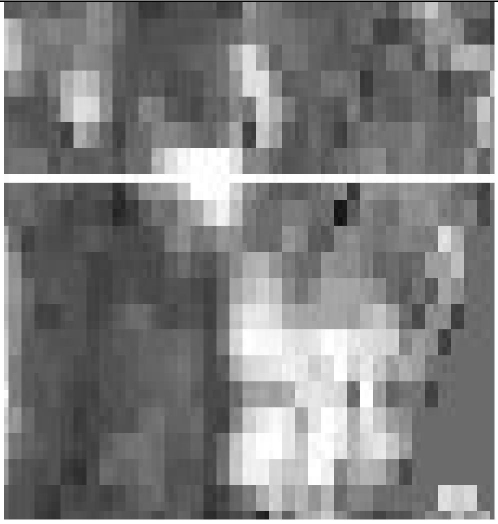
M711 (1:50 000) topographic map in WGS84 UTM32. Updated 1990. © Statens Kartverk. Center position: 5 74 250E, 65 62 900N





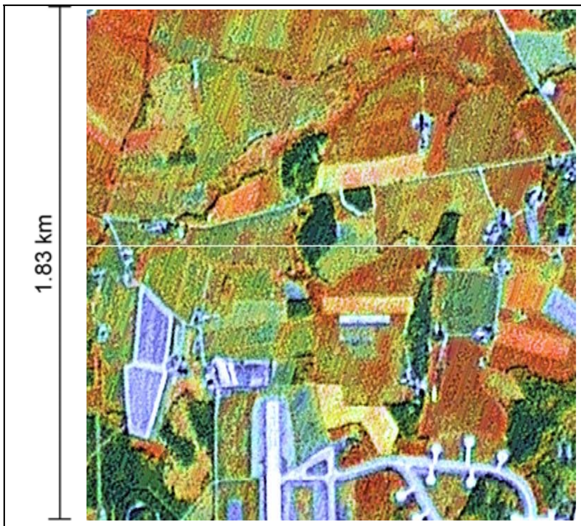
DifferenceImage = XDEM-N5





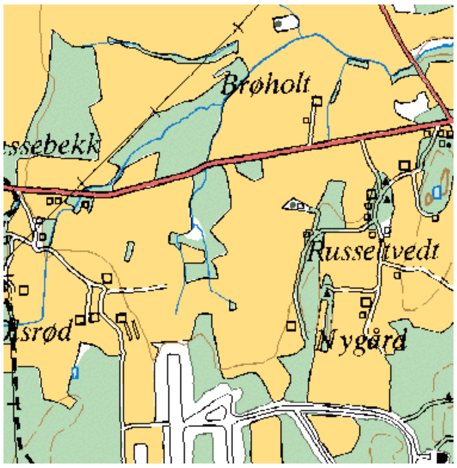
DifferenceImage = CDEM1-N5

Figure 7.22 A dense coniferous forest East of Sandefjord Airport Torp. The white horizontal lines in the images show the location of the profiles drawn in the two plots. Average DEM difference between the two SRTM systems over the central forest area is 1.94 m, with the X-band DEM showing the higher elevations.

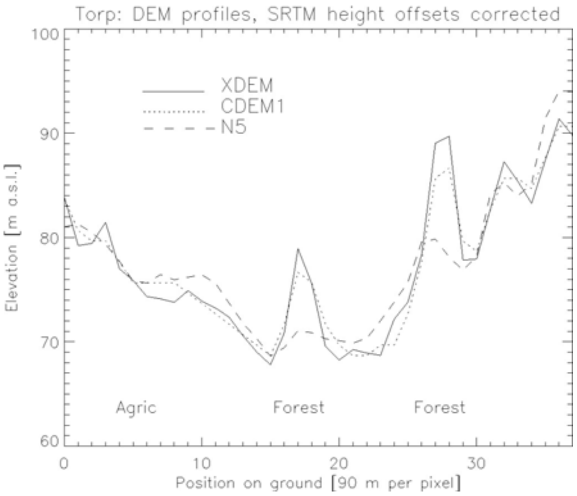


IRS-1C satellite image.

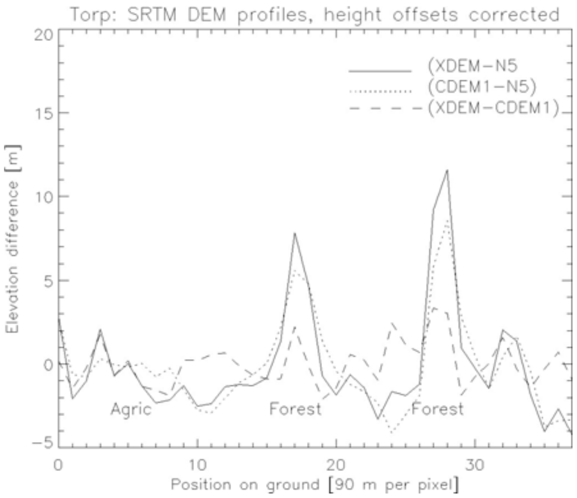
© Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997

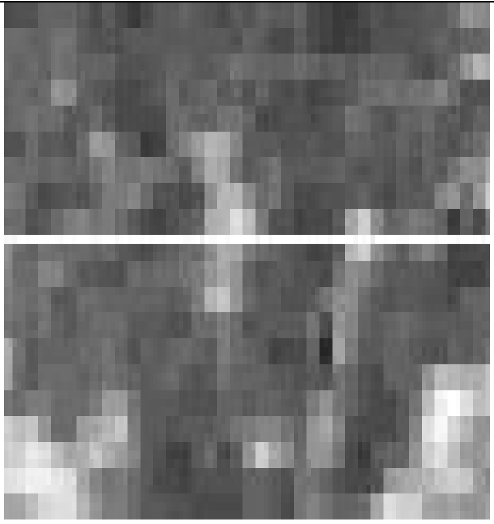


M711 (1:50 000) topographic map in WGS84 UTM32. Updated 1990. © Statens Kartverk. Center position: 5 72 080E, 65 63 520N



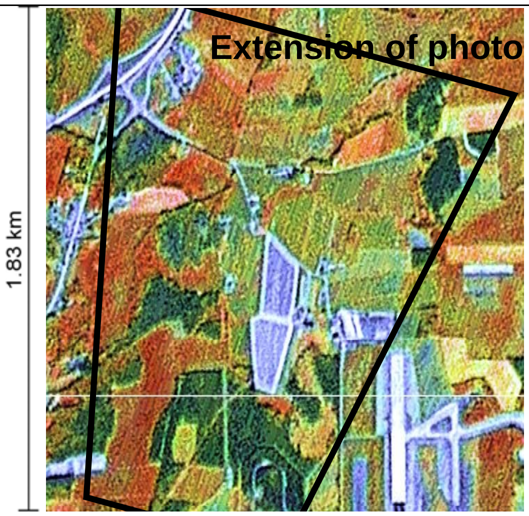
DifferenceImage = XDEM-N5



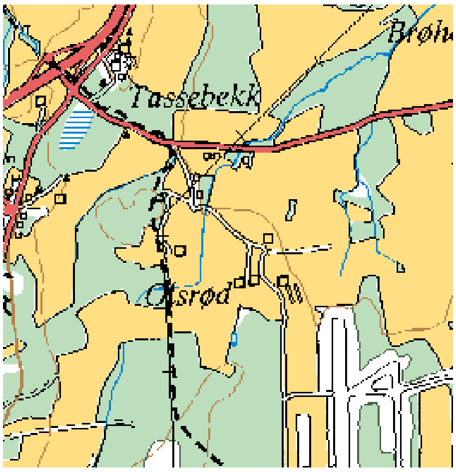


DifferenceImage = CDEM1-N5

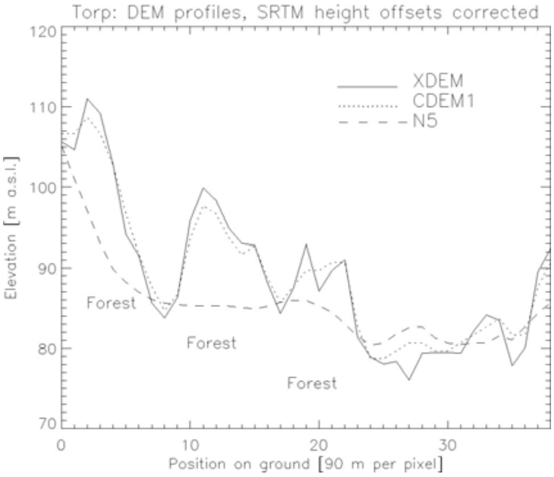
Figure 7.23 A dense coniferous forest North of Torp Airport, Sandefjord. The white horizontal lines in the images show the location of the profiles drawn in the two plots.

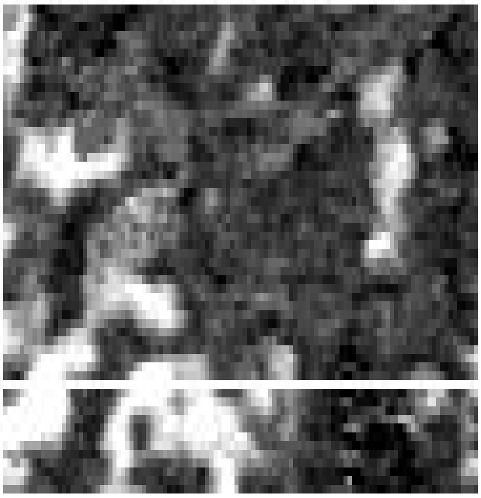


IRS-1C satellite image.
© Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997

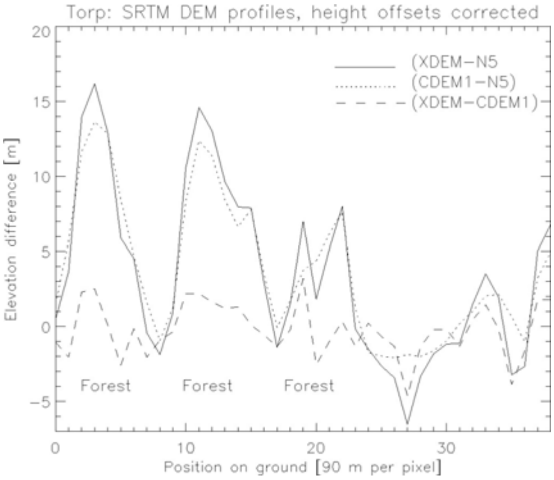


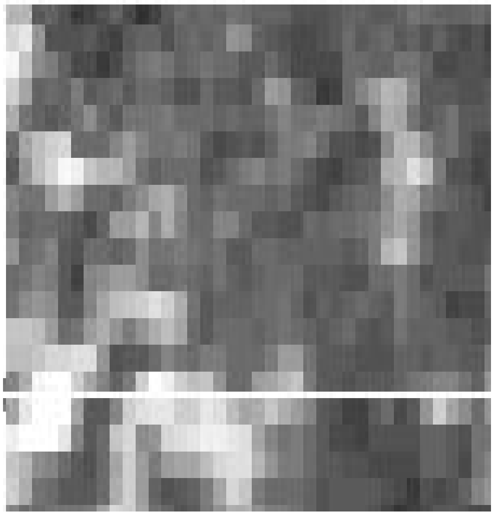
M711 (1:50 000) topographic map in WGS84 UTM32. Updated 1990. © Statens Kartverk.
Center position: 5 71 430E, 65 63 290N





DifferenceImage = XDEM-N5

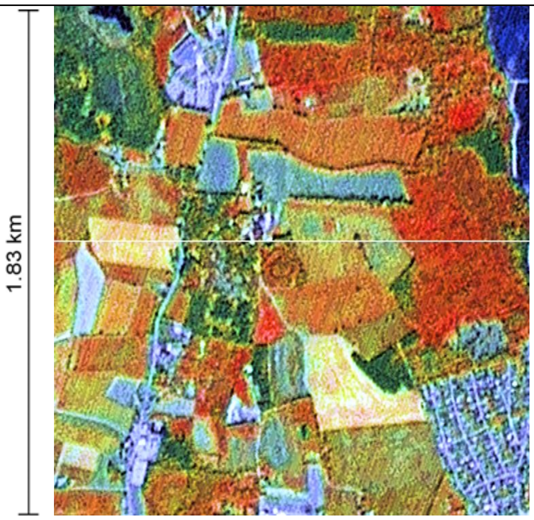




DifferenceImage = CDEM1-N5

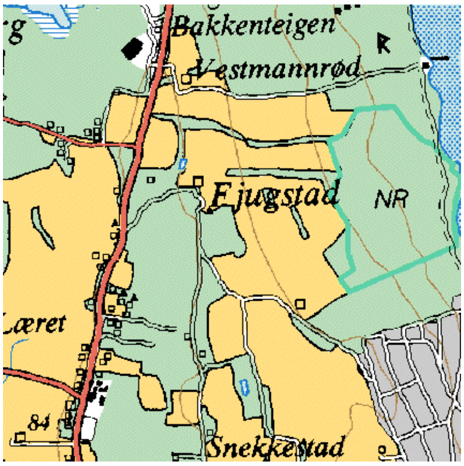
Figure 7.24 *Several dense forest areas northwest of Torp airport, Sandefjord. The horizontal lines in the images show the location of the profiles drawn in the two plots. The rectangle substituted inside the IRS-1C image corresponds to the photo in Figure 7.25.*

Figure 7.25 *Aerial photo taken in February 2000 (© FFI 2000) over an agricultural landscape northwest of Sandefjord Airport Torp in Vestfold, Norway. Refer this photo to the SRTM data, maps and satellite image in Figure 7.24.*

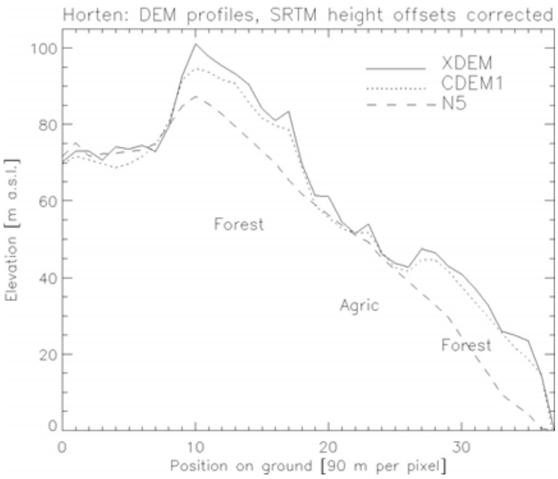


IRS-1C satellite image.

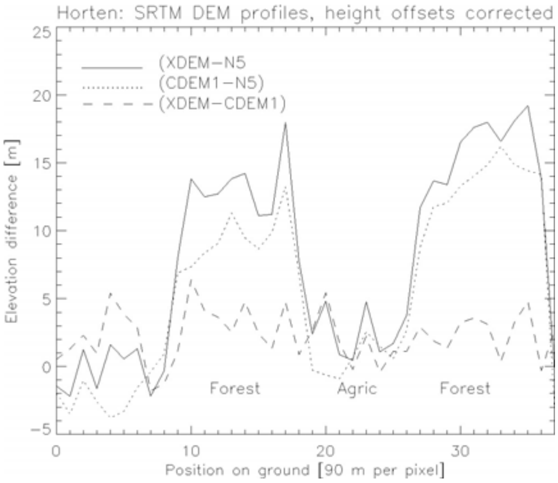
© Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997

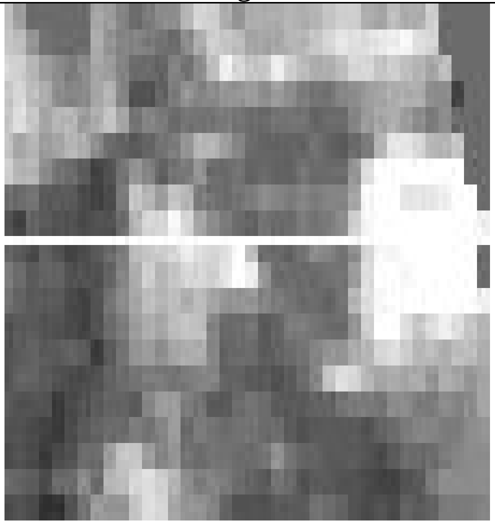


M711 (1:50 000) topographic map in WGS84 UTM32. Updated 1990. © Statens Kartverk.
Center position: 5 82 350E, 65 81 270N



DifferenceImage = XDEM-N5





DifferenceImage = CDEM1-N5

Figure 7.26 Two dense forest areas south of Horten city. The horizontal lines in the images show the location of the profiles drawn in the two plots. Average SRTM difference over the two central forest areas along the profile is estimated to 3.15 m (left) and 2.58 m (right).

7.7.5 Gravel pits

In certain places in Vestfold there are clusters of SRTM DEM data with elevation values 20 to 35 meters *lower* than the N5 reference map! Several of these clusters are found at the location of gravel pits. The reason is that the N5 reference map has not been updated for years! It will therefore be the SRTM DEM from year 2000 that represents the more recent ground elevations in these areas.

A large gravel pit West of Stokke town clearly depicts this situation. Reference maps from Stokke stamp mill are shown in Figure 7.27, while the remote sensing data and profile plots are given in Figure 7.28. Clearly, the N5 reference map has not been updated for many years, but show the contour lines from the original landscape! In this situation, the SRTM DEM will give a much better representation of the ground elevations across the gravel pit.

Now, if we assume that the reference DEM refers to the original natural ground surface elevations, it will be possible to estimate the amount of rock removed by the stamp mill activity during its existence. For the Stokke stamp mill, we estimated a DEM volume difference of 1.74 million m^3 using the “90 m unedited” C-band DEM. Only samples with an absolute *elevation difference* larger than 10 m is used in the statistics (i.e. the threshold is set to the specified relative vertical accuracy for this SRTM product). The local pixel spacing is approximately 92.7m x 47.4m. Similarly, we estimated a volume of 1.77 million m^3 using the “30 m” X-band DEM. Now, only samples with an absolute *elevation difference* larger than 6 m was used in the statistics (i.e. the specified relative vertical accuracy for this SRTM product). The local pixel spacing is approximately 30.9m x 15.8m. Overall, one may regard a conservative production estimate for the Stokke stamp mill to be 1.7 million m^3. So far, it has not been possible to confirm this estimate with the owners of this stamp mill.

In Table 7.14, the excavated volume is estimated for four more stamp mills, also located in Vestfold, Norway. The N5 reference DEM from these stamp mill areas all seem to reflect the original situation *before* the stamp mill production started. Clearly, the stamp mills at Stokke and Fokserød have produced the largest gravel pits.

The examples with the stamp mills and gravel pits clearly show that high-resolution DEM produced from spaceborne InSAR platforms can be used on a regular basis to indicate/estimate the amount of man-made activities in an area.

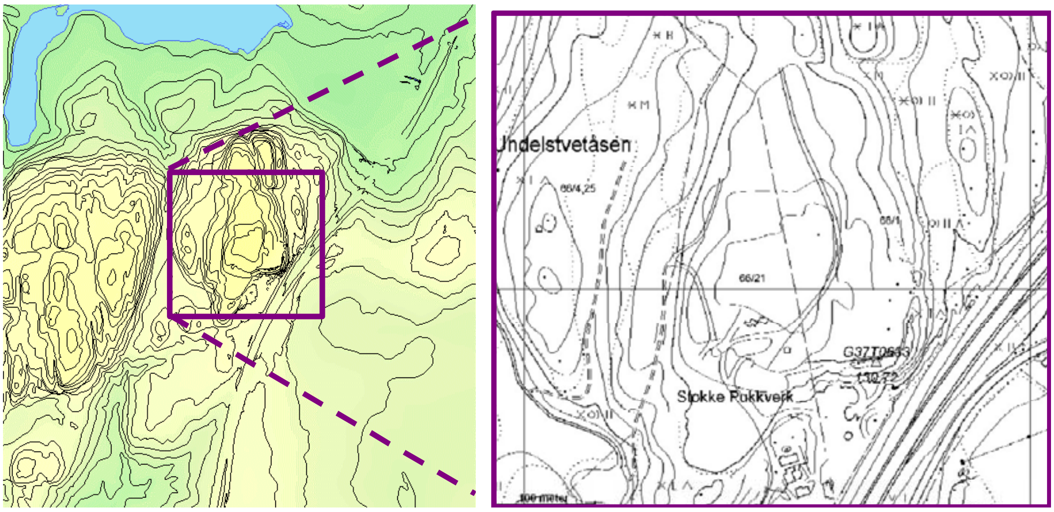
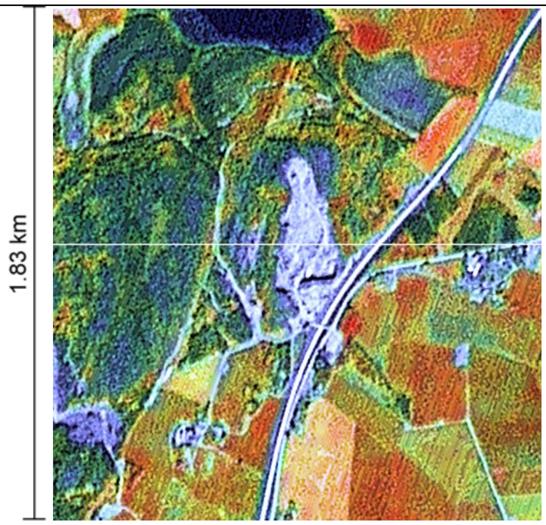


Figure 7.27 ***Left:*** *N5 digital vector map.* ***Right:*** *Analogue version of the N5 map. The N5 data are used to produce the N5 digital raster DEM that in turn is used as input to the SRTM difference analysis, see Figure 7.28. Original N5 maps: © Norwegian Mapping Authority 2002.*

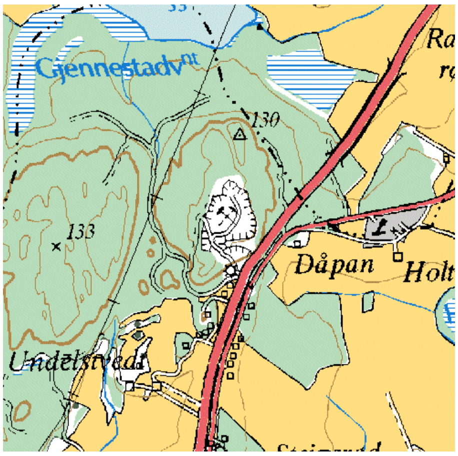
Name of nearest town or farm	**Comment**	**Coordinates (WGS84, UTM zone 32)**	**Maximum elevation difference value (SRTM X-band DEM – N5 DEM)**	**Estimated total volume of rock removed**
Stokke, Andebu	The N5 map seems to have original terrain contours	5 71 310E 65 65 810N	-37 m	1.8 M m³
Fokserød, Sandefjord	The N5 map seems to have original terrain contours	5 68 750E 65 60 000N	-36 m	1.2 M m³
Sønset, Andebu	The N5 map seems to have original terrain contours	5 64 540E 65 79 060N	-21 m	0.3 M m³
Hovet, Re	The N5 map seems to have original terrain contours	5 63 000E 65 87 850N	-21 m	0.6 M m³
Brandsrud, Lardal	The N5 map seems to have original terrain contours	5 53 740E 65 87 580N	-18 m	0.5 M m³

Table 7.14 *Estimated stamp mill activity by means of SRTM X-band DEM and an old reference DEM representing the original terrain. The total volume of rock removed (millions of m³) by several stamp mills located all around Vestfold County in Norway.*

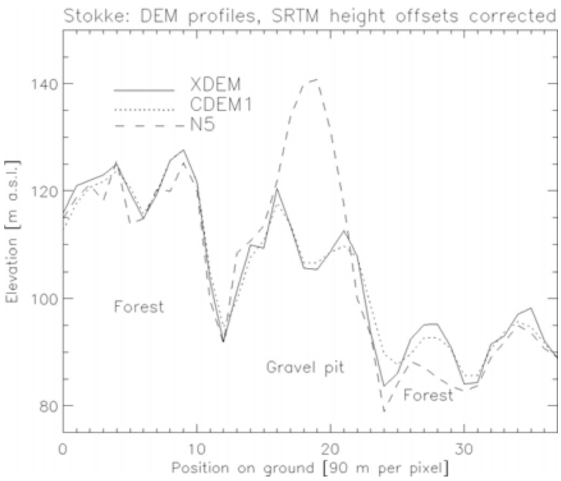


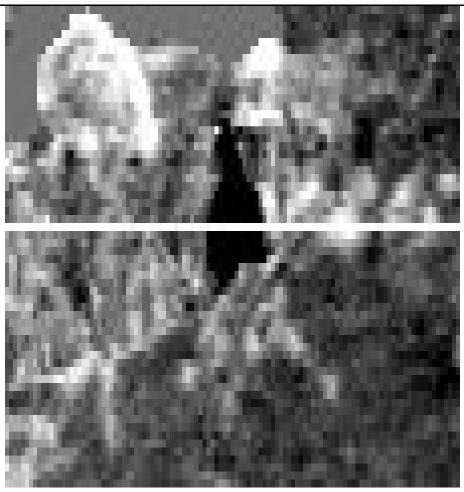
IRS-1C satellite image.

© Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997

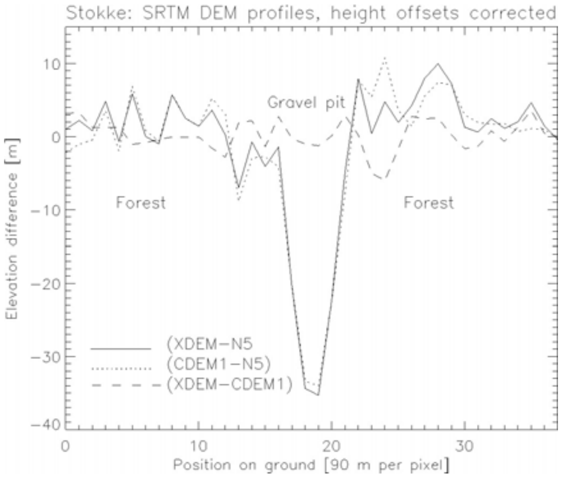


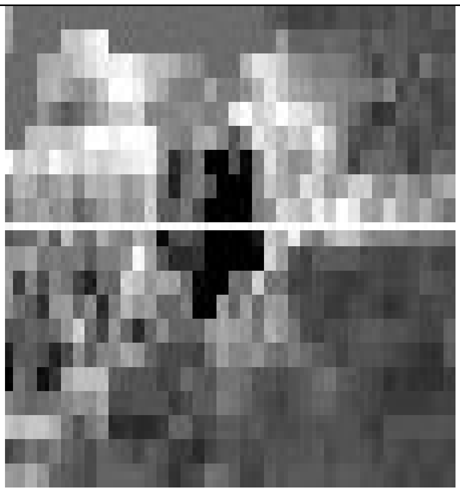
M711 (1:50 000) topographic map in WGS84
UTM32. Updated 1990. © Statens Kartverk.
Center position: 5 71 310E, 65 65 810N





DifferenceImage = XDEM-N5



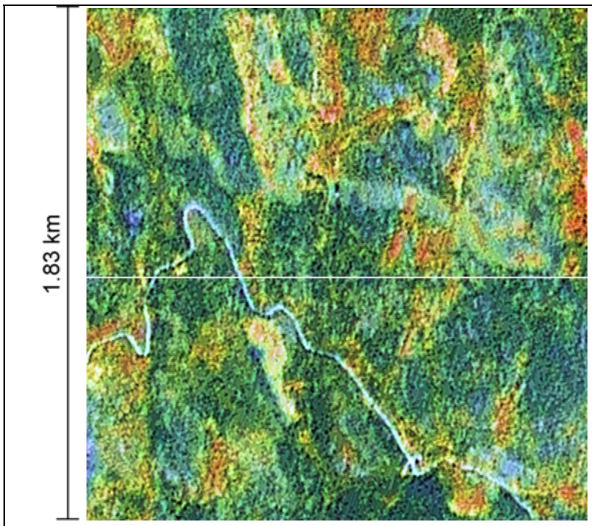


DifferenceImage = CDEM1-N5

Figure 7.28 *A large gravel pit with a stamp mill next to the motorway E18 and 2 km west from Stokke town, Vestfold. The horizontal lines in the images show the location of the profiles drawn in the two plots. Clearly, the elevation contours in the N5 reference map have not been updated for many years!*

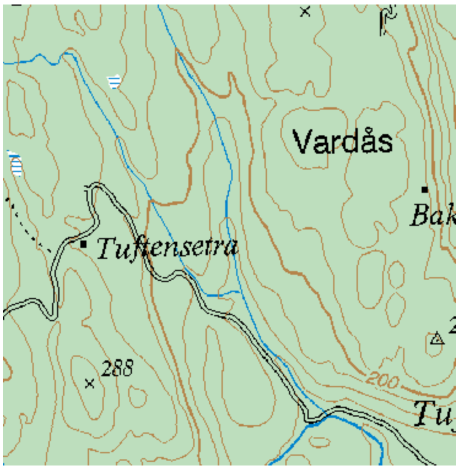
7.7.6 Detecting errors in the N5 reference map

A large elevation difference (SRTM X-band DEM – N5 DEM) of more than –21 m was also observed at Vardås in Re, Vestfold. A set of images and plots are shown in Figure 7.29. First, this difference was attributed to a possible stamp mill site producing a large gravel pit. But now, the IRS-1C image from 1997 did not show any sign of a gravel pit, only forest. May this indicate a brand new stamp mill production site? Perhaps. However, going back to the original contours in the N5 vector map clearly showed that *parts of some contour lines were labeled with elevations as much as 40 meters too high* – and this in an area where a stream cuts through the landscape! So, even after removing many errors spotted in the N5 data earlier on (see chapter 6.4), some errors are obviously still present in the N5 dataset. This shows that the SRTM DEM can be used in an effective manner to pinpoint areas where the reference DEM (yes, even a *high-resolution* reference DEM…!) may need updates.

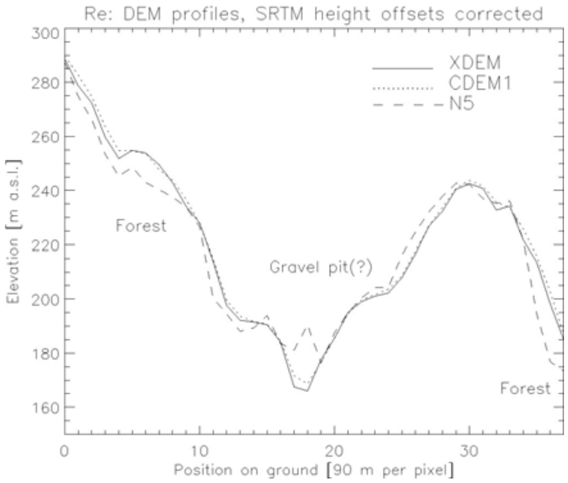


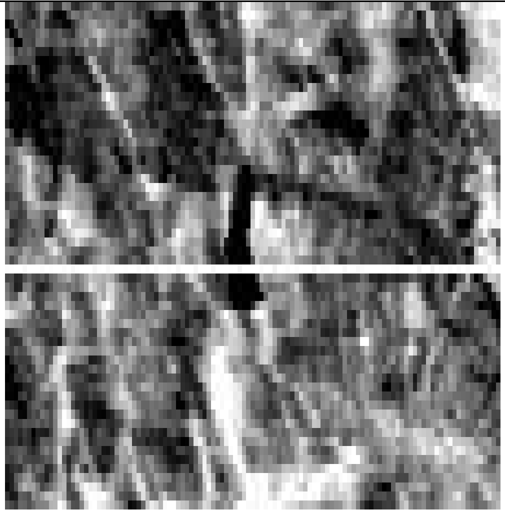
IRS-1C satellite image.

© Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997

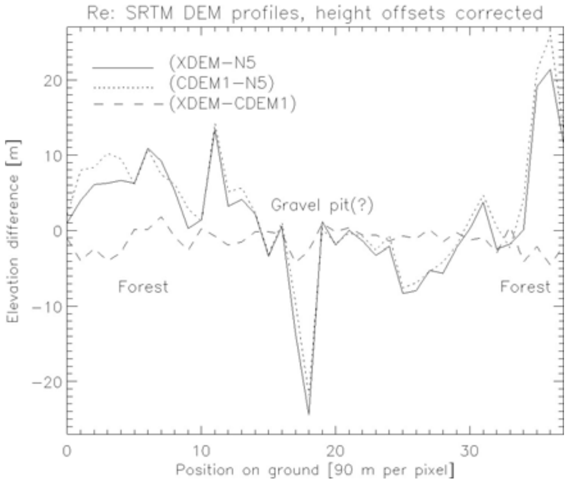


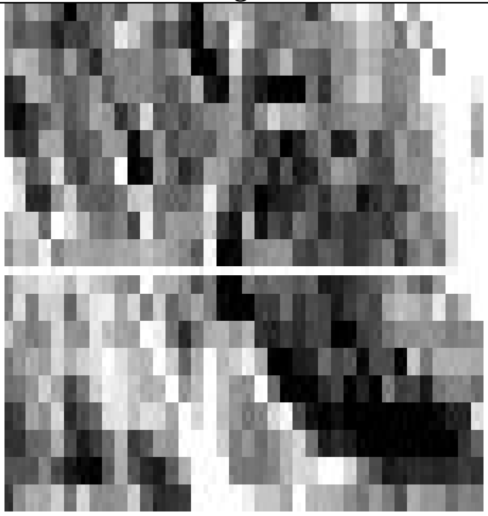
M711 (1:50 000) topographic map in WGS84 UTM32. Updated 1990. © Statens Kartverk. Center position: 5 62 260E, 65 85 270N





DifferenceImage = XDEM-N5





DifferenceImage = CDEM1-N5

Figure 7.29 *A large depression spotted in the difference DEM image. Location is near to Vardås in Re, Vestfold County. The horizontal lines in the images show the location of the profiles drawn in the two plots. In this example, the depression is caused by 10-40 m errors in the elevation contours of the N5 reference map!*

7.7.7 Sandefjord Airport Torp

One may think that quite accurate interferometric elevation heights can be obtained from a runway at an airport. However, as we shall see underneath, the opposite may be true.

Sandefjord Airport Torp is located north of Sandefjord city in Vestfold County, Norway. It has one runway and several taxiways. The SRTM HEM from DLR indicates larger elevation errors from the runway than from the surrounding agricultural fields and forest stands, see Figure 7.30 c). The largest errors are linked to the locations with lowest SAR backscatter and thus the highest HEM values. This is clearly seen when comparing Figure 7.30 a), b) and c).

These relationships are investigated in more detail by plotting some profiles along the runway as shown in Figure 7.31. These profiles of the SRTM X-band SAR backscatter, the HEM values, the X-band DEM, and the N5 reference data show that height errors of several meters are indeed present over the runway. The reason is that low SAR backscatter will give a low S/N ratio. This will in turn lead to higher uncertainties in the interferometric elevation estimate (i.e. higher HEM values).

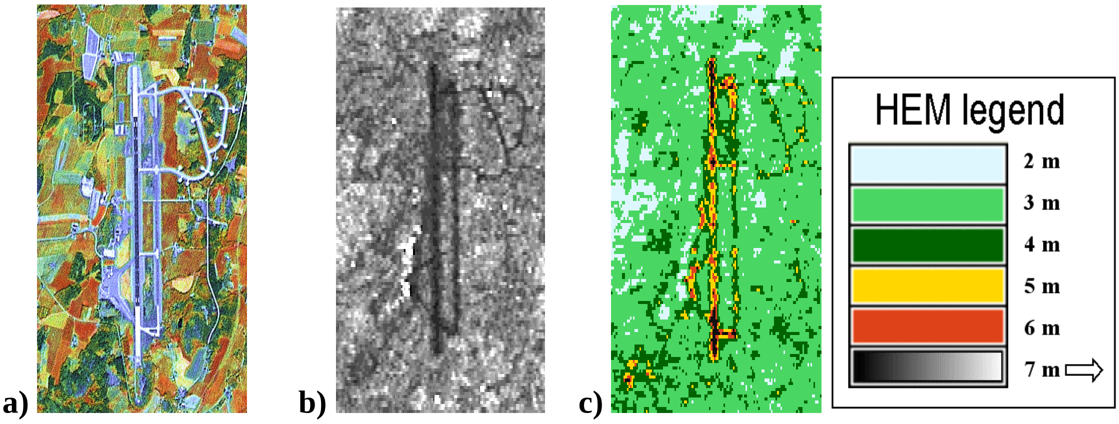


Figure 7.30 Sandefjord Airport Torp near to Sandefjord city in Vestfold County, Norway. a) IRS-1C satellite image (© Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997). b) SRTM X-band SAR image taken 14 February 2000 (© DLR 2003). c) SRTM X-band HEM (© DLR 2003).

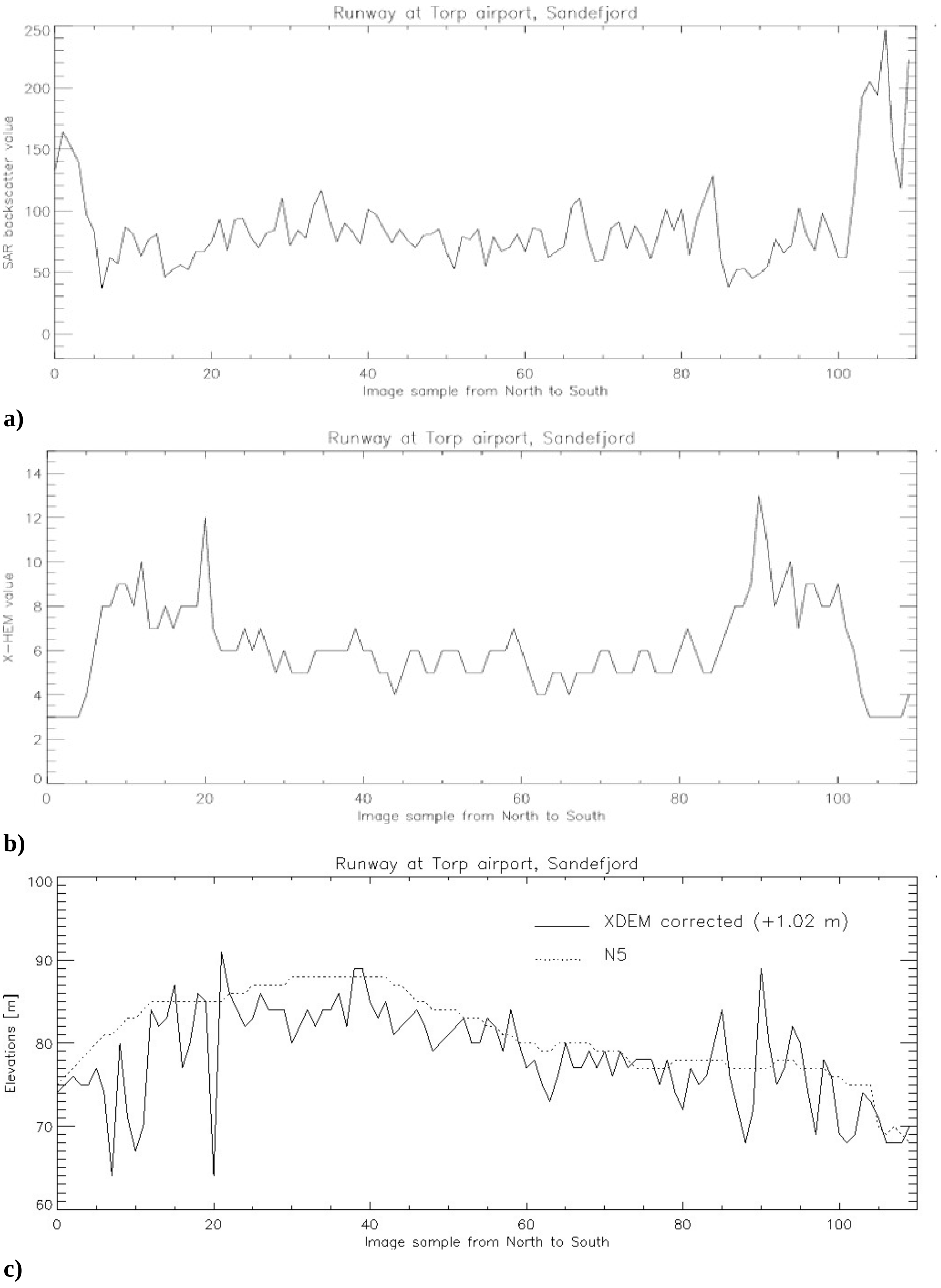
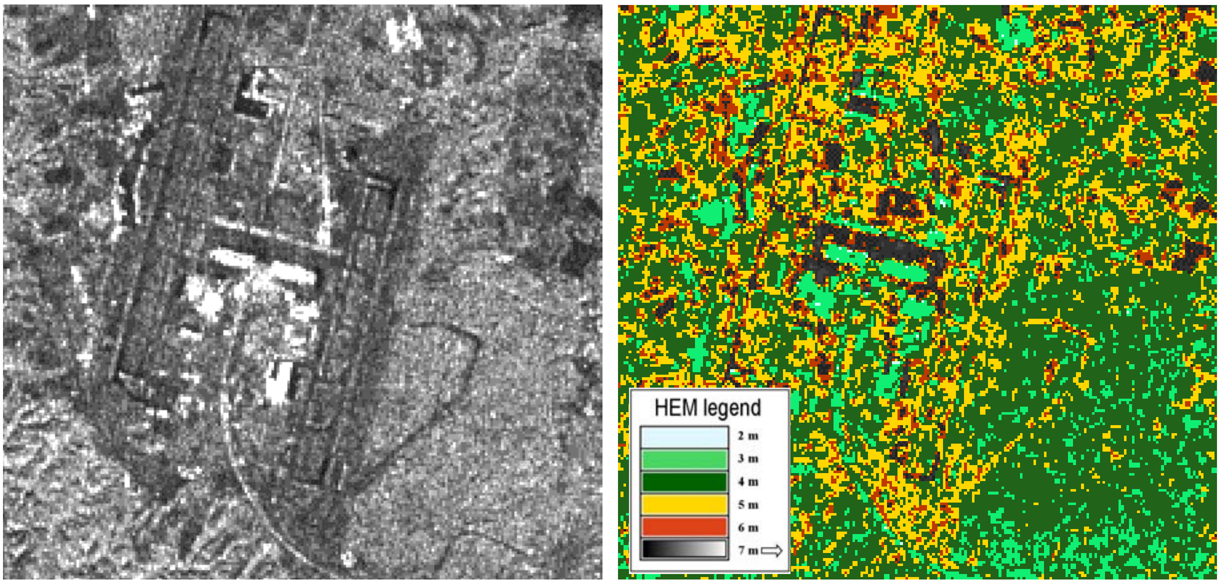


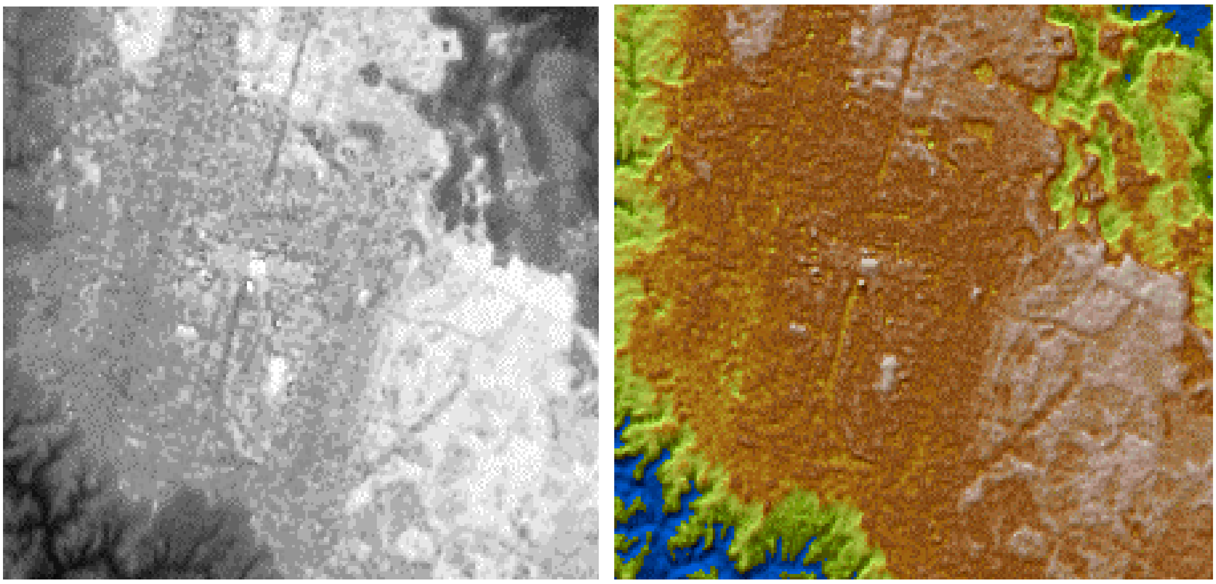
Figure 7.31 Profiles taken along the runway at Sandefjord Airport Torp. a) The SRTM X-band SAR backscatter from 14. February 2000. b) The HEM profile gives estimated interferometric error values up to 13 m. c) There are large differences between the SRTM X-band DEM and the N5 data, especially in areas with high HEM values.

7.7.8 Oslo Airport Gardermoen

Oslo Airport Gardermoen is not located in the Vestfold County test area, but North of Oslo. However, SRTM X-band data covering both Oslo and Gardermoen were also made available by DLR for this project. The different SRTM X-band data are shown in Figure 7.32. The SRTM X-band DEM was resampled from geographic coordinates to UTM zone 32 with 25 m pixel spacing using cubic convolution. It was also corrected from its original WGS84 ellipsoid heights to geoid heights using the NGA/NASA EGM96 model, but not corrected for any vertical bias offset prior to the analysis performed in this section.



SRTM X-band SAR image, 19 February 2000. Colour-coded SRTM X-band HEM image.



SRTM X-band DEM. Colour-coded painted relief of the SRTM X-band DEM.

Figure 7.32 SRTM X-band data from Oslo Airport Gardermoen, Norway. The painted relief DEM is using USGS colour LUT with 3 m intervals coded from 165 m a.s.l. to 240 m a.s.l.

The strong SAR backscattering areas have the lowest HEM-values. The strong SAR backscatter will typically come from man-made objects (hangars, buildings, infrastructure), but also the coniferous forest areas (e.g. lower right quadrant of images in Figure 7.32). The dense coniferous forest clearly has an elevation higher than the ground when measured by the SRTM X-band system: typical numbers here are in the range from 10 m to18 m above the ground level.

Some large structures seem to give a distinct elevation in the SRTM X-band DEM. These structures are hangars or buildings. The elevation heights (meters above sea level) for some of these buildings are indicated with yellow labels in Figure 7.33. All these elevation heights are gathered from a high-resolution vector map of the area.

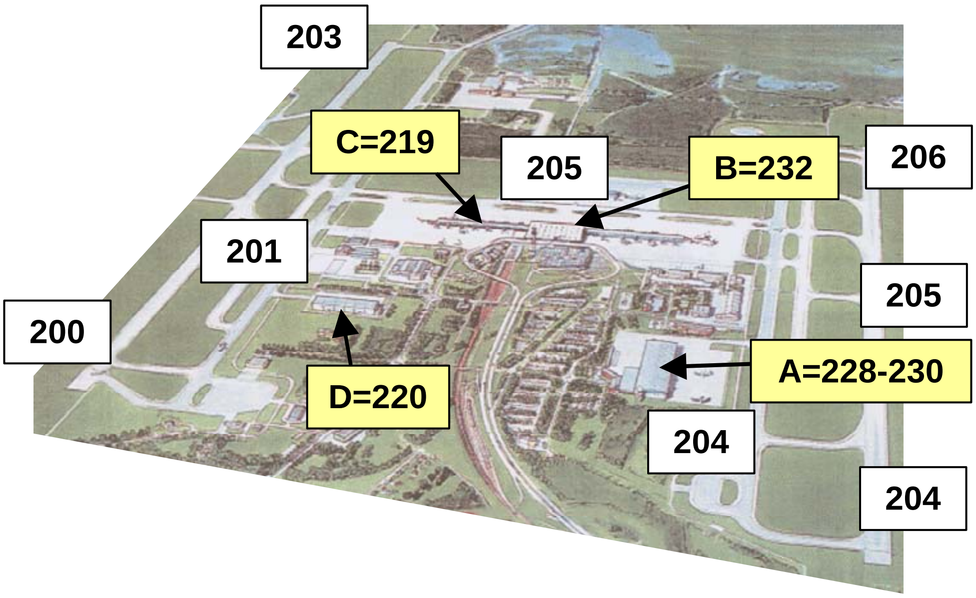
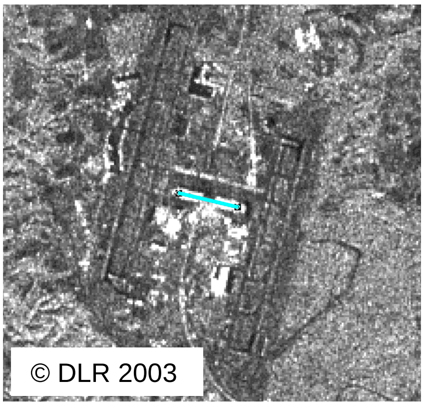


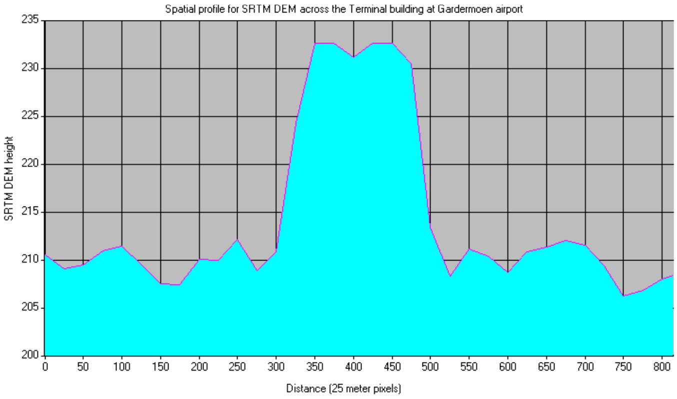
Figure 7.33 Drawing of Oslo Airport Gardermoen. The numbers labelled in white are elevation heights (meters above sea level) at ground level, while numbers in yellow are building roof elevation height (meters above sea level).

The results from analysing the yellow coloured labelled objects in Figure 7.33 are as follows:

A. Large hangar along the eastern runway. Map data indicate that the roof is approximately 25 m above the ground level, with an absolute height of 228 m along the roof edge, and 230.3 m at the central part of the roof. This hangar is clearly seen in the SRTM DEM, and the elevations range from 226 m to 229 m a.s.l for the central roof structure. This is surprisingly correct with only 1-2 m vertical offset at certain pixel positions along the hangar central roof structure! The SRTM DEM is able to measure the height of this hangar to within 10 % of its real height.

B. Main terminal building. The top roof structure of this building is 27 m above the ground, or 232.5 m a.s.l. The highest SRTM DEM values from this building are 232 m a.s.l. A very good match indeed! See also the 2D plot below stretching from the western terminal across the main terminal and over to the eastern terminal as indicated in the SRTM X-band SAR image to the left:





C. Terminal building stretching out to the West and East where we find the airplane piers. The very top structure of the roof is 219 m a.s.l. The highest SRTM DEM values obtained from the central roof structure are in the range from 207 m to 212 m a.s.l. The SRTM system underestimates the height of this building by 10 m, but at the same time indicates an elevation that is 2-7 m above the ground surface (205 m a.s.l.), see also the 2D plot above. The reason for the error can be that this part of the terminal building is only 30 m across, thus the 25 m pixel size may not be enough to resolve individual parts of the main roof structure. Investigating the SAR image again, it shows that strong SAR backscatter covers 7 pixels across (i.e. 175 m). The map measures 100 m across both the airplane piers and the building (35 m + 30 m + 35 m), see the aerial photo below:

From this it can be concluded that the strong SAR backscatter comes from the terminal building, piers and airplanes/vehicles. Now, spatial averaging is performed in the InSAR processor. The relatively small SRTM elevation heights in this area will therefore reflect the *average* InSAR elevations obtained from *all* these man-made structures of different heights.

D. Hangar near to the western runway. This building is 19 meters tall. The SRTM DEM indicates that the building is from 15 m to 19 m tall. In other words, the SRTM X-band InSAR system is able to estimate the elevation of this building to within 20 % of its correct height.

7.7.9 Building heights in city areas

SAR backscatter from a building may originate from structures that are elevated from the ground. In the case of SRTM, a tall building with a certain extension will therefore probably give a higher elevation value than the surrounding ground surface if there are structures on the roof that are acting as corner reflectors.

The SRTM DEM has a spatial resolution of approximately 30 m. Higher spatial resolution would be required if one considers using the InSAR technique to map building heights in an urban area. However, it is worth investigating if SRTM elevations in urban areas are linked to particularly large buildings.

Sandefjord city centre in Norway has several large office buildings, hotels, shopping malls and warehouses. The N5 reference dataset is also available from this area. Figure 7.34 shows that the SRTM elevations vary throughout the city centre area. These elevation differences (Figure 7.34c) are compared to the aerial photo in Figure 7.35. Some of the SRTM elevation differences are up to 9-12 m. These seem to come from areas having large building complexes of several storeys.

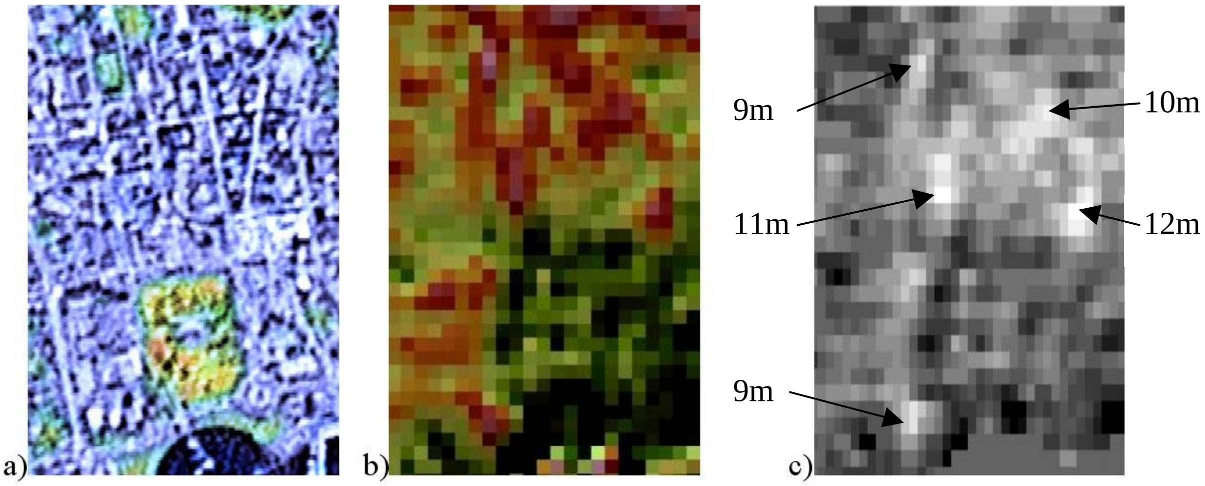


Figure 7.34 Sandefjord city in Norway. a) IRS-1C satellite image (© Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 199). b) SRTM X-band DEM with colour intervals of 1 m. c) SRTM difference image (X-band DEM - N5 DEM) showing grey levels in the range from –12 m (black) to +12 m (white).

A complex building structure with a lot of corners will most likely give a strong SAR backscatter regardless of the radar beam aspect- and incidence angle. It will then be possible to estimate building heights using the InSAR technique. This is the situation for some of the buildings in Sandefjord city.

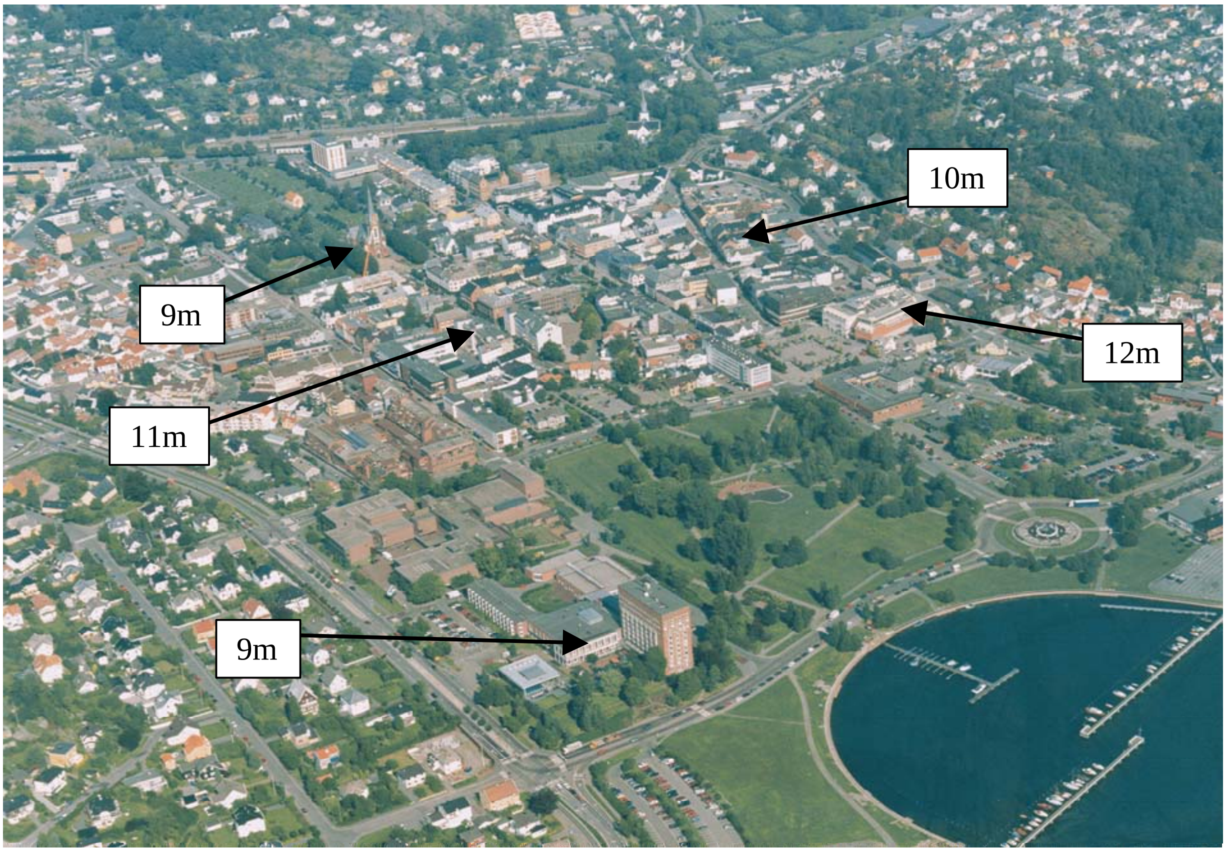


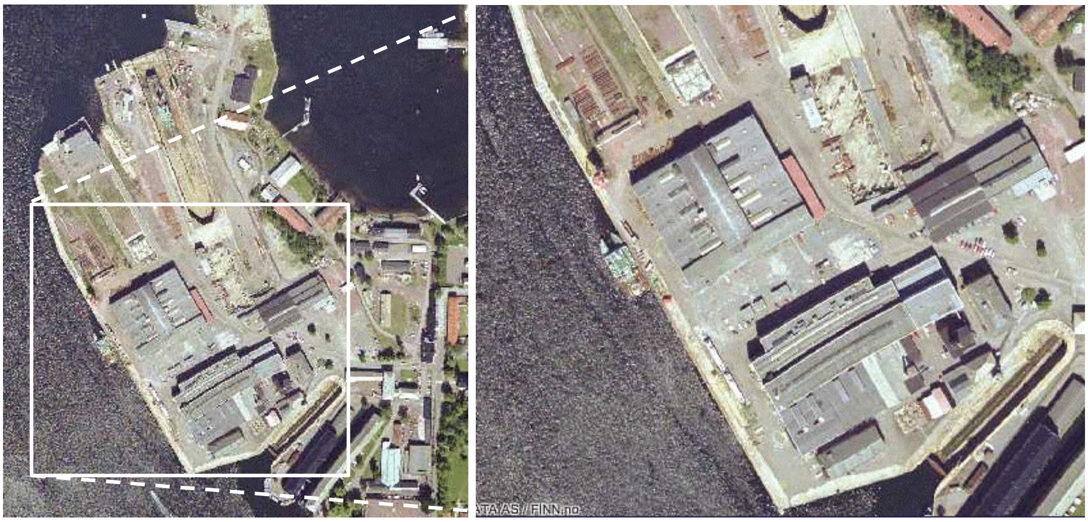
Figure 7.35 Airphoto over Sandefjord city. © FFI 1999.

Other large and tall buildings within the SRTM test area did not give a significant contribution to the SRTM elevation heights. Such buildings can be residential houses, but also large industrial warehouses with e.g. a flat roof. In any case, the building structure is such that the SAR backscatter signal is relatively small. This is the reason why large buildings may “hide” in an InSAR measurement.

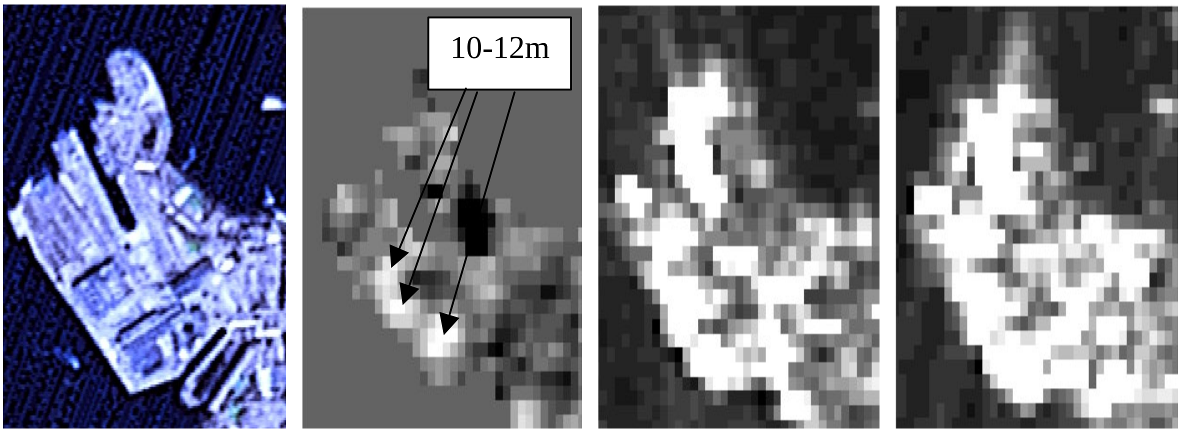
SRTM can therefore not in general be used to map building heights, but may in some cases give interesting measurements from certain buildings. In fact, mapping forest heights with SRTM is more reliable than mapping building heights. The main reason is that forest stands are not as directionally sensitive as hard man-made objects. Also, forest stands will normally extend over larger areas than buildings. Forest areas will therefore retain the elevation estimate better when spatial averaging is performed during the InSAR processing.

7.7.10 Building heights in a harbour

Horten city has several harbours. One of the harbours has large warehouses and wharfs. Many of the man-made features in this harbour show up with strong SAR backscatter in two SRTM X-band SAR images taken in February 2000, see Figure 7.36. These two SRTM X-band SAR images were taken on the 14th and 16th of February in an ascending and descending pass respectively. They therefore image the same man-made features with different aspect angles. However, as seen in Figure 7.36, many features give a strong SAR backscatter regardless of viewing geometry. These man-made objects consist of many complex structures and corners. We notice that the SRTM difference DEM in Figure 7.36 show up with SRTM elevations that are up to 10-12 m above the ground level (when referring to the N5 reference DEM). This fits very well with the location of the large buildings that are 15-20 meters tall in this area of the harbour [T. Bjørke 2005]. However, in this example, the SRTM system seems to underestimate the building heights by as much as 5-8 m.



Aerial photo, © GEODATA/FINN.no.



IRS-1C image SRTM difference DEM SRTM X-SAR, 14 Feb. SRTM X-SAR, 16 February.

Figure 7.36 SRTM data from a harbour in Horten, Norway. The SRTM difference DEM is made by subtracting the N5 data from the X-band DEM, and then substituting a sea mask. The grey level in the SRTM difference DEM is in the range from –20 m (black) to +12 m (white). IRS-1C image: © Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997. Original SRTM X-band data: © DLR 2003.

The dark spot seen in the SRTM difference DEM indicates an area in the harbour with elevations down towards –20 m below the ground! Now, the N5 DEM gives a ground elevation of 10 m, while the SRTM X-band DEM shows elevations down towards –10 m. There seems to be a mismatch between these two datasets. The N5 DEM may be wrong, or there has been digging in the ground before the SRTM acquisition. These questions may be resolved in the future by carrying out field observations.

7.7.11 Oil refinery

Slagentangen oil refinery is located northeast of Tønsberg city in Vestfold, next to the Oslofjord. This refinery consists of many large and tall tanks, a harbour area, and the plant itself with many metal structures, corners and pipes. An aerial photo was taken over the area in august 1999, see Figure 7.37. An N50 DEM (scale 1:50000) was used when analysing the SRTM DEM from the Slagentangen oil refinery since no N5 data was available from this area.

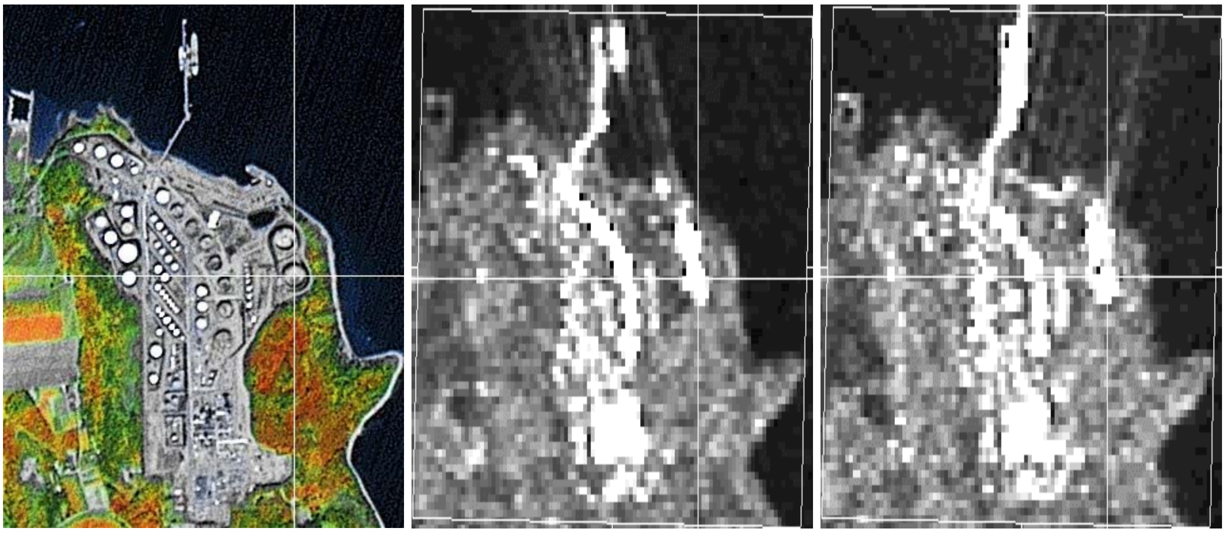
The SRTM X-band SAR backscatter is shown in Figure 7.38 together with the SRTM DEM, difference DEM and a profile. The 14. February X-band SAR image is taken in an ascending pass while the 16. February image is taken in a descending pass. It is evident that most of the larger man-made objects give a strong SAR backscatter regardless of aspect angle.

The dense old forest areas lead to an SRTM elevation height that is 10-16 m above the ground, see the SRTM difference DEM image and profile in Figure 7.38.

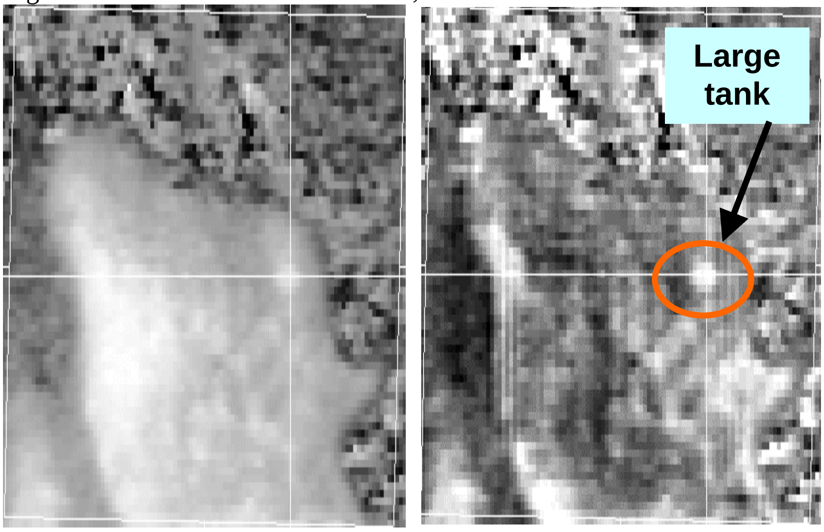
Most of the tanks in the refinery are more than 10 m high. However, only a few of them seem to introduce an extra elevation height in the SRTM DEM. One of these tanks is located in the eastern part of the refinery. The top structure of this tank measures between 12 m and 18 m above the ground in the SRTM DEM, see the marked cross on the images in Figure 7.38, and also the corresponding 2D-profile going from West to East over the images.

So, although the man-made structures in the oil refinery do give a strong SAR backscatter, the backscatter may not come from structures actually representing the upper surface of the object. Another way to look at it is that averaging (in the InSAR processor) over the various man-made structures may not necessarily lead to an elevation that represents the *very height* of the structure. This is particularly so when operating at spatial resolutions in the 20 m to 30 m range (e.g. these high-resolution SRTM X-band data). The consequence is that dense old forest areas will more likely give a higher elevation (i.e. elevations up towards 15-20 m above the ground level) than spatially scattered man-made objects (e.g. buildings separated by roads).

Figure 7.37 Aerial photo taken over Slagentangen oil refinery. © FFI 1999.



IRS-1C image SRTM X-SAR, 14 Feb.2000 SRTM X-SAR, 16 Feb.2000.



SRTM X-band DEM SRTM X-band difference DEM

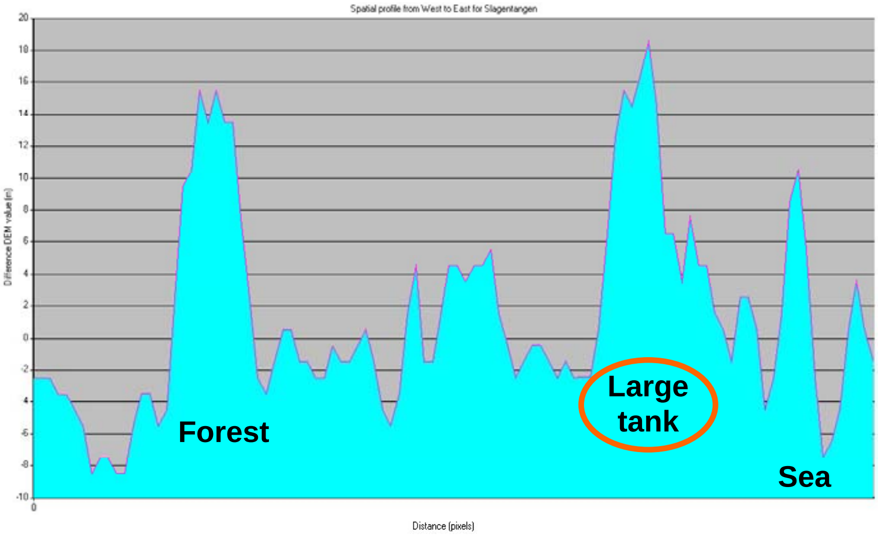


Figure 7.38 *SRTM X-band SAR images, DEM, SRTM difference DEM, and an optical satellite image from IRS-1C. North is up on the images. IRS-1C image: © Statens Kartverk 1998, Antrix, SIE, EUROMAP, OM&M 1997. SRTM X-SAR image: © DLR 2003.*

8 RESULTS FROM BYKLE

The Bykle test area represents elevations in the range from sea level and up to 1486 m above sea level. More details of this test area are found in chapter 3.2. The Bykle test area has no large cities, but a few small towns are present at lower elevations. Another characteristic of this area is that there are hardly any trees above 900 m elevation. In this sparse mountainous landscape, there is at present no high-resolution digital elevation map (i.e. the N5 data). However, the coarser N50 digital elevation data is available for the whole region together with trigonometric points and spot heights.

8.1 Using the N50 DEM as reference

The overall accuracy of the N50 DEM was estimated to 5.0 m (RMSE) over agricultural fields, see chapter 6.6. This RMSE value may seem small, but is in fact *larger* than the RMSE value estimated for the SRTM X-band DEM (3.4 m) and the SRTM C-band DEM (4.6 m). The results from comparing several different DEMs with each other are given in Table 8.1. In fact, even an inter-comparison of the two SRTM DEM types will give a smaller RMSE (2.7 m) than what is obtained from the N50 DEM! More details of the SRTM DEM statistics can be found in Table 7.9.

Reference DEM	**DEM used to investigate the vertical accuracy**	**Vertical accuracy, RMSE [m]**	**The vertical accuracy, 90 % confidence level calculated (i.e. RMSE*1.649) [m]**
N5	SRTM X-band	3.4	5.6
N5	SRTM C-band	4.6	7.6
N5	N50	5.0	8.2
SRTM X-band	SRTM C-band	2.7	4.5

Table 8.1 Vertical accuracy over agricultural areas in Vestfold using different DEM sources. The DEMs are in geographic coordinates resampled to a common pixel spacing of 0.0008333 degrees (i.e. approximately 90x45 m for the Vestfold test site).

These results should be kept in mind when analysing the vertical accuracies from the Bykle test area. In other words, one should naturally expect a *slightly poorer result* when using the coarser N50 DEM as the reference dataset, instead of the N5 data. So, if the difference between the SRTM DEM and the reference DEM is found to be *larger* over rolling topography in the mountainous Bykle area than agricultural fields in Vestfold, this does not necessarily mean that the SRTM system does a poor job over mountainous regions, only that larger uncertainties may have been introduced due to the coarser N50 reference DEM.

8.2 Preprocessing the data

The following data sets are available for the Bykle test area:

- SRTM X-band DEM and X-band HEM (“30 m” data)
- SRTM X-band SAR image taken 16 February 2000
- SRTM C-band DEM (unedited “90 m” data)
- N50 raster DEM
- NGA/NASA EGM96 geoid model
- Landsat-7 TM image taken 6 August 1999
- Water level recordings from hydroelectric dams (obtained from Norwegian Water Resources & Energy Directorate.

All the SRTM DEMs, maps and satellite images are converted to WGS84 geographic coordinates (Lat/Lon) using the SRTM C-band DEM “90 m” grid spacing (i.e. a pixel spacing of approximately 92.8 m x 47.4 m, see Table 4.1). The N50 DEM is shown as a painted relief in Figure 8.1. The “90 m” unedited SRTM C-band DEM is shown in Figure 8.2, where *data voids* are marked in red. These *data voids* seem to originate from areas of extreme slopes (radar shadow or layover effects) or water bodies. This will be studied in more detail in the next chapters.

The SRTM X-band DEM and HEM were first transformed from the WGS84 ellipsoid to the local geoid using the NGA/NASA EGM96 geoid model. The X-band data was then averaged (3x3 pixels) to fit with the C-band DEM representation (3 arc-second data points). The X-band DEM and HEM are shown in Figure 8.3 and Figure 8.4 respectively. The HEM data are colour-coded, and the largest HEM-values are approaching 100 m over the Bykle test site.

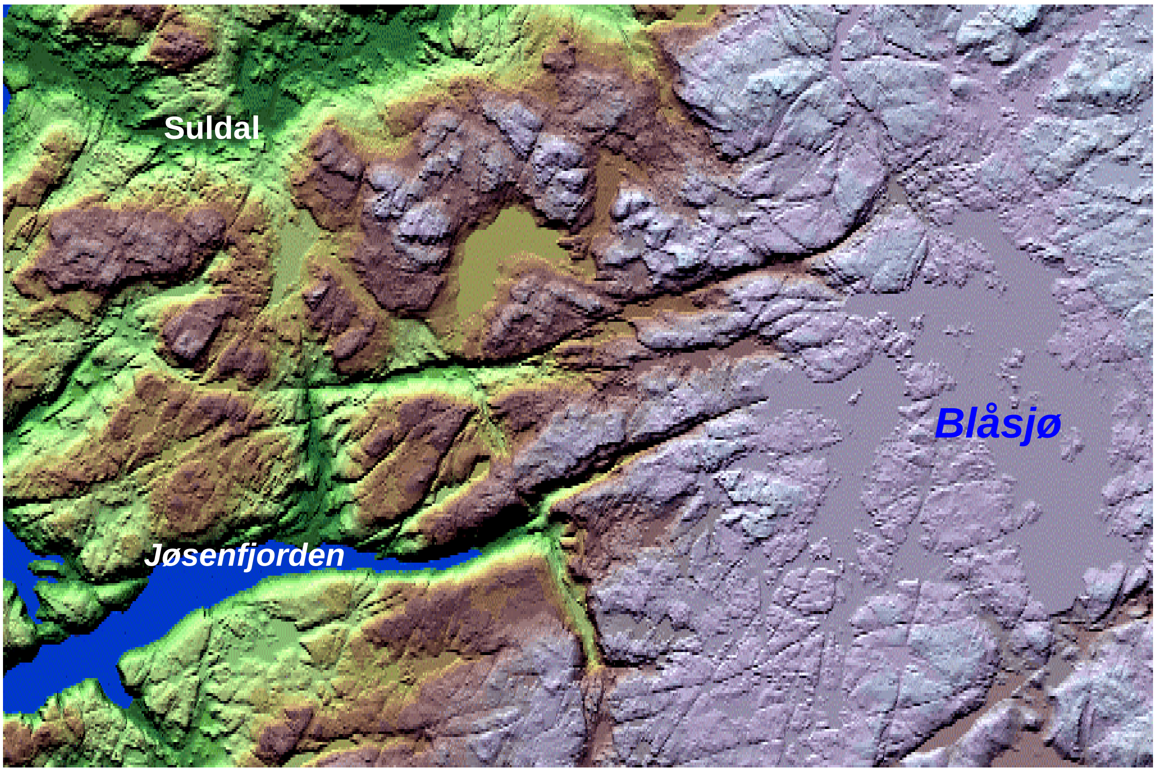


Figure 8.1 N50 DEM data from Bykle test site in Norway. The painted relief representation is using USGS colour LUT with 25 colours stretching from sea level (blue) to 1480 m a.s.l. Original N50 DEM data: © Norwegian Mapping Authority.

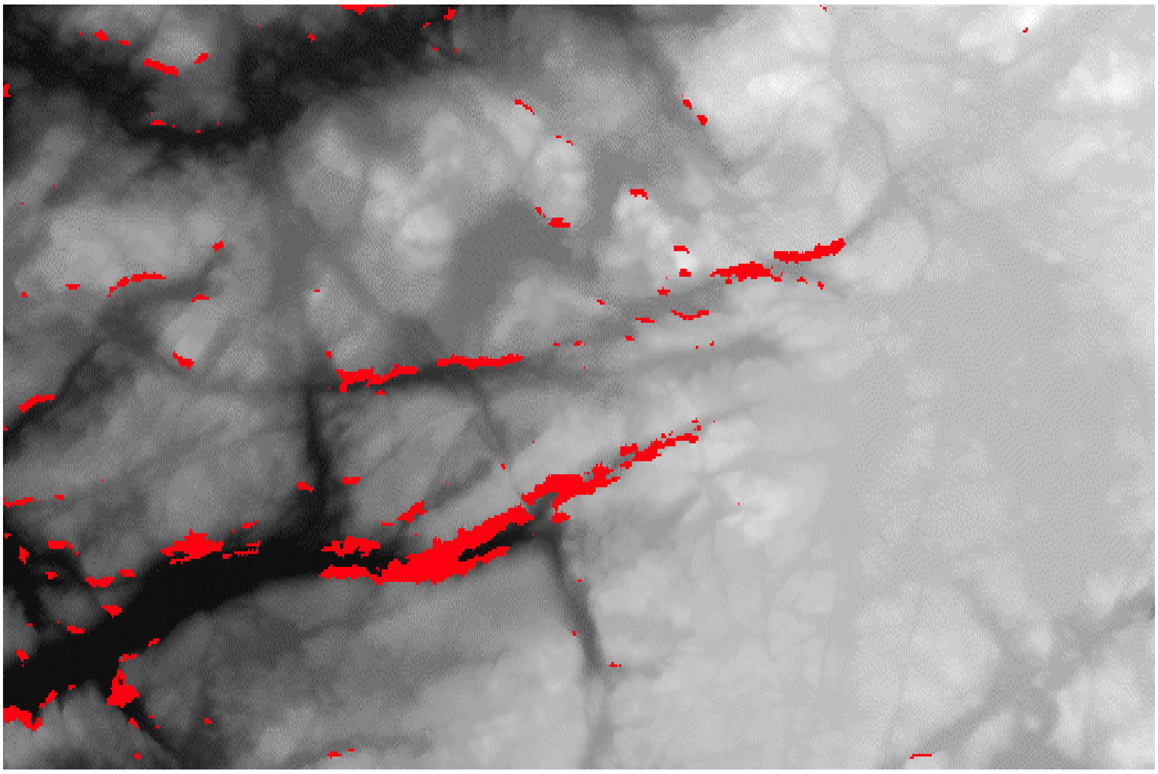


Figure 8.2 SRTM C-band DEM ("90 m" unedited data) from Bykle. Void data caused by open water, shadowing, or phase unwrapping anomalies are flagged with the value -32768 in the DEM, and are here shown in red colour. © NASA/JPL 2004.

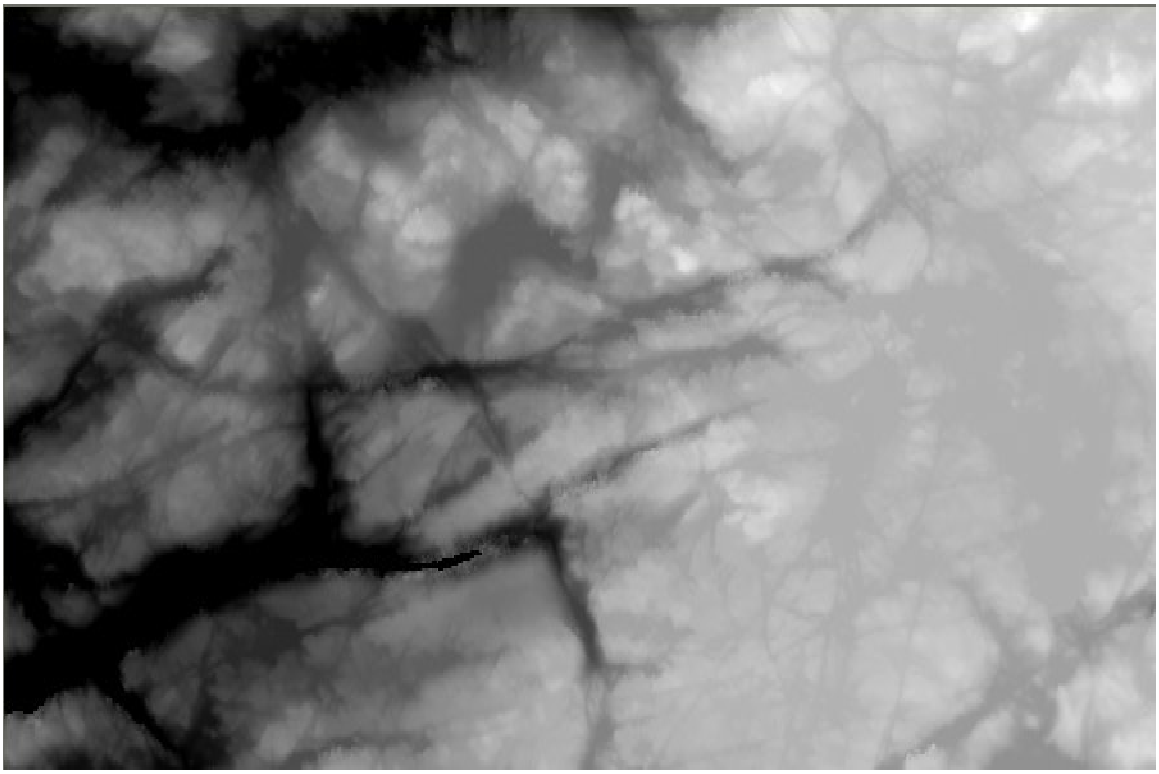


Figure 8.3 SRTM X-band DEM ("30 m" data) from Bykle test site in Norway. © DLR 2003.

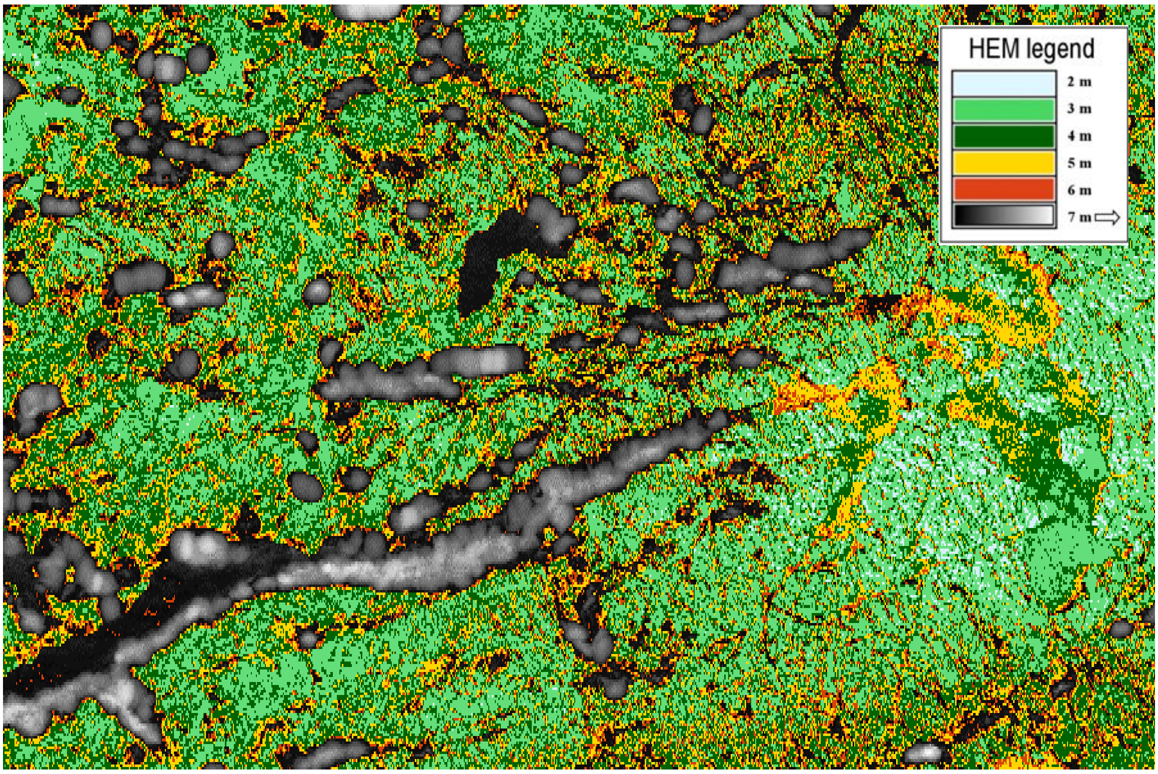


Figure 8.4 Colour-coded SRTM X-band Height Error Map (HEM) from Bykle test site in Norway. The largest HEM-values (light grey) are approaching 100 m in this region. Original SRTM HEM data: © DLR 2003.

8.3 Calibrating SRTM DEMs using water level recordings

The SRTM DEMs from the Vestfold test area were corrected for a small vertical bias (see chapter 7.4.4 and 7.5) using N5 heights from agricultural fields. Would this vertical bias also be present for the Bykle test area located approximately 220 km to the West? How can a possible vertical offset (bias) be estimated when there are no agricultural fields and it is the coarser N50 DEM (with its limitation with respect to elevation accuracy, see chapter 8.1) that is available?

No corner reflectors were deployed in Bykle during the SRTM mission. GPS measurements could therefore not be used. Alternatively, trigonometric points and spot heights may be obtained from the Norwegian Mapping Authority. These data have vertical accuracies better than 1 meter. However, these reference points in the terrain are often located at small peaks. This will certainly introduce errors when performing a spatial averaging over several pixels in the “90 m” or “30 m” SRTM DEMs.

One plausible solution is to average the SRTM elevations from a large lake surface. If the SAR backscatter from the lake surface is low, then the InSAR estimate may be poor. However, if the wind is making the water surface rough, or if the lake is frozen in wintertime, the SAR backscatter may be strong enough to give a good InSAR estimate. The lakes high up in the mountains in Bykle were frozen at the time of SRTM acquisitions in February 2000. The average dam elevation can therefore be used to estimate the vertical bias.

The true water level from a lake may be different from what is found in the N50 DEM or on paper maps. This is especially so in Bykle where many of the large lakes are *hydroelectric dams* with water levels that may vary by several meters a year. Now, the Norwegian Water Resources & Energy Directorate (NVE) records water levels from hydroelectric dams in Norway with cm accuracy on a daily basis. These measurements may be compared directly to the SRTM elevations obtained from the same water surface. NVE supported FFI with water level measurements from 10 of the dams in the Bykle area [R Engeset 2004]. It was decided to use the NVE water level recordings from the 16th February 2000, since these were taken in the middle of the SRTM mission.

The water levels of the dams can be estimated from the SRTM DEMs by averaging over several pixels within the dam. The averaging is here performed over rectangular regions of interest (ROIs). The ROIs are selected so that they avoid dam shores and small islands. In this manner, no terrain pixels are included in the evaluation. The ROIs are established by visual inspection of the SRTM X-band SAR image, the Landsat TM image and the N50 DEM. There are no SRTM C-band *voids* included in these ROIs. The SRTM X-band HEM values vary from 3 m to 21 m for these ROIs, with the majority of HEM values being less than 7 m.

The mean and standard deviation of the SRTM water levels are estimated using the ROIs. Results are presented in Table 8.2, which shows water levels for the ten hydroelectric dams in the Bykle test area. The names of the dams are given together with the letters A to J. These letters are also plotted in the map in Figure 8.5 to indicate the dam location.

The dam level indicated on paper maps will often give the total span of water levels (e.g. 1055-930 m for Førrevann). The level found in the N50 DEM refers to the maximum filling level of the dam. The true water levels in February 2000 were from 1 m to 6 m *lower*. The estimated *mean SRTM dam elevations* correspond very well to the NVE water level recordings! The standard deviation of the SRTM C-band dam elevations vary from 0.6 m to 1.5 m for these nine dams, while it varies from 0.9 m to 3.7 m for the X-band DEM data.

The smallest *vertical offset* (i.e. mean SRTM dam elevation – NVE water level recording) are obtained from the C-band system with values spanning from –0.7 m to +0.6 m. Now, averaging over all these nine elevation differences leads to a mean of 0.16 m with a one standard deviation of 0.41 m for the C-band data. On the contrary, the X-band system gives a vertical offset that is slightly higher: values spanning from –4.8 m to +2.0 m, with a mean (over the nine dams) of –0.42 m and a standard deviation of 1.98 m. The RMSE is also estimated over all nine dams. This gives a value of 0.42 m and 1.95 m for the C-band and X-band systems respectively.

Name of dam/lake	Dam level shown on paper maps [m]	N50 DEM [m]	**NVE** water level recordings in February 2000 [m]	Mean **SRTM** elevation from dam surface [m]		Vertical offset (**SRTM – NVE**) [m]	
				C-band	X-band	C-band	X-band
A: Svartevatn	899-780	899	892.81	892.41	889.98	-0.4	-2.8
B: Storvann	1055-930	1055	NA	1050.02	1049.32	NA	NA
C: Vassbottvatn	475-470	475	471.21	471.78	470.07	0.6	-1.1
D: Førrevann	1055-930	1055	1050.19	1050.55	1050.17	0.4	0.0
E: Stovedalsvatn	831-	831	830.21	829.56	828.86	-0.7	-1.4
F: Oddatjørn	1055-930	1055	1050.15	1050.63	1051.25	0.5	1.1
G: Sandsavatn	605-550	605	601.20	601.51	602.10	0.3	0.9
H: Mosvatn	518-516	518	516.25	516.64	512.00	0.4	-4.3
I: Lauvastølvatn	605-590	605	601.37	601.42	602.81	0.1	1.4
J: Suldalsvatn	70	70	67.52	68.00	69.50	0.5	2.0

Table 8.2 Several data sources show water levels for ten hydroelectric dams in the Bykle region, Norway. Maps indicate water level heights, but these heights may deviate from the true value by several meters. The Water Resources & Energy Directorate (NVE) in Norway made water level recordings with cm accuracy on 16 February 2000. The mean SRTM elevations are estimated from extended areas within the dams. The SRTM C-band DEM gives very small elevation differences indeed, when referring to the NVE measurements.

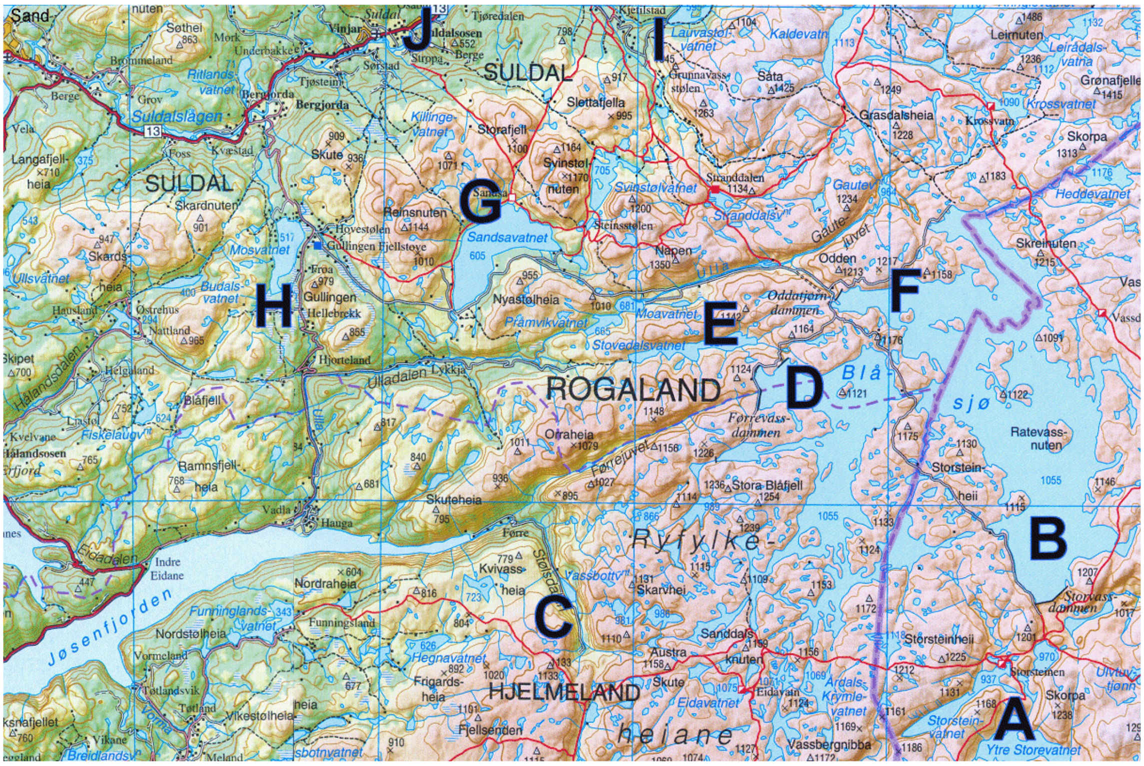


Figure 8.5 *Map over the 1180 km² (42.6 km x 27.7 km) large test area near Bykle in south Norway. The locations of the ten hydroelectric dams studied in this paper are indicated with letters from A to J. © Statens Kartverk/Kunnskapsforlaget Det Store Norgesatlas 2003.*

The SRTM DEMs are generally corrected for any vertical offset (bias) by the processing facilities at JPL and DLR. This calibration is performed using ground control points, coastlines, and the 1 km grid GLOBE DEM. It is reported that the absolute elevation difference between the X- and C-band data is less than +/- 6 m for much of the globe, and that a mean difference value of –0.89 m is found for Europe [Marschalk *et al.*, 2004]. The result in Bykle shows that the average elevation difference between the two SRTM systems (i.e. vertical offset) is only 0.58 m when estimating over all the hydroelectric dam surfaces.

The water surface at the hydroelectric dams was most probably covered by ice during the SRTM acquisition in February 2000. There are no *in-situ* data on the state or thickness of the ice or the snow cover. However, if we assume that the ice thickness is less than 1 m, then the difference in absolute elevation may be contributed to different radar scattering phase centers in the snow/ice volume. It is known that the C-band system may penetrate slightly deeper into the volume than the shorter wavelength X-band system. The penetration depth will also depend on the temperature and volumetric moisture content. However, there is no consistent trend in the elevation difference obtained from the two SAR systems (compare the two right columns in Table 8.2). So, unless the different dams have different ice thickness and are covered by various snow types, the ice and snow cover cannot explain the non-systematic vertical offset differences.

Figure 8.6 indicates that the SRTM X-band system covered the Bykle test site three to five times during the 11 days mission. The C-band system did probably cover the same region eight to ten times due to its four times wider ScanSAR swath. The smaller standard deviation of the C-band elevations may therefore come from the fact that more scenes are averaged during the InSAR processing. Rabus *et al.* (2003) confirm this when stating: “the X-SAR DEM reaches its optimum qualities of < 1 m vertical accuracy when more than 10 orbits are covering a given point on the ground”. This may also be the reason for why the C-band system is closer to the true dam elevations (a difference from –0.7 m to +0.6) than the X-band system (a difference from –4.8 m to +2.0 m).

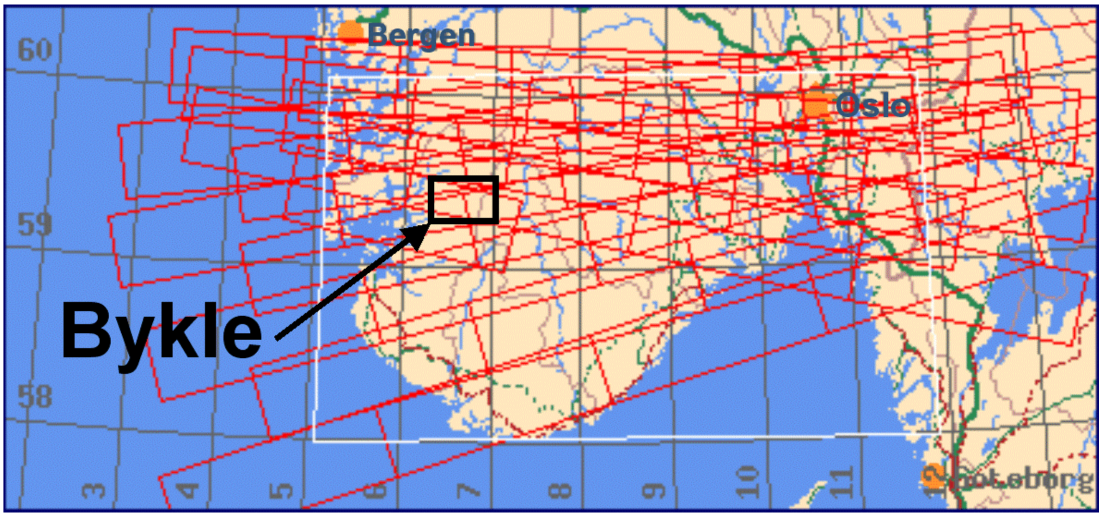


Figure 8.6 The Bykle test site in South Norway used for the SRTM AO-038 project. Screen dump is taken from the DLR EOWEB and shows the SRTM X-band SAR swaths.

In general, the results from estimating the vertical offset show that the SRTM system is very well calibrated. It should therefore not be necessary to perform any vertical offset corrections of the Bykle data set.

The results also clearly show that it is feasible to use the water levels from hydroelectric dams to calibrate the SRTM system, or even other spaceborne InSAR systems in the future. If we now assume that a spaceborne system is calibrated to < 1 m vertical accuracy, then it will also be possible to monitor the water level of hydroelectric dams all around the World with sub-meter accuracies. This is indeed an attractive application for authorities and the operators of hydroelectric power stations that may like to have knowledge of the water levels in surrounding dams. Monitoring water levels of hydroelectric dams in this manner may very well be performed at regular time intervals by polar orbiting InSAR systems in the future.

8.4 Making a water body mask

In the previous chapter, it was clearly shown in Table 8.2 that the water level of lakes in the reference DEM (N50) might differ from 1-6 m. Since some of the dams are quite large, it would be an advantage to mask out the water bodies *before* estimating the RMSE for the two SRTM DEMs in the region. The N50 DEM did not support a water level mask. However, a Landsat-7 TM image was taken over Bykle in August 1999, see Figure 8.7.Although this satellite image has several clouds present, a fairly good water body mask can be made for the majority of lakes/dams in the area.

A water body mask was made after applying an ISODATA cluster routine on the full Landsat-7 TM dataset (i.e. all the 7 bands). The parameter setting for the ISODATA clustering was as follows: 25 clusters, 10 iterations and a confidence level of 0.95. The result is shown in Figure 8.8 where the cluster number *one* will represent water surfaces.

These ISODATA water clusters are combined with the sea and fjord pixels (zero elevation) obtained from the N50 reference DEM, to construct a complete water body mask. This mask is used in the evaluation of the SRTM DEMs that are presented in the next sections.

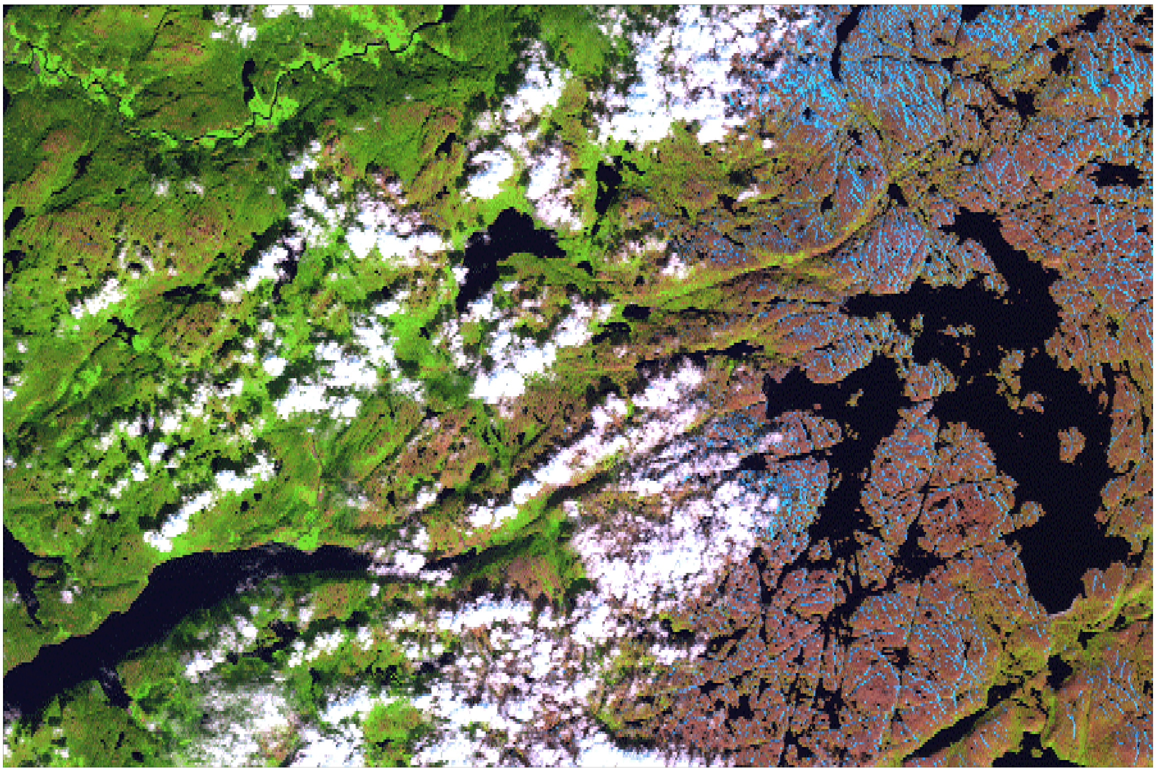


Figure 8.7 Landsat-7 TM image (band 5-4-1) from the Bykle test site in Norway. This image was acquired on the 6th of August 1999.

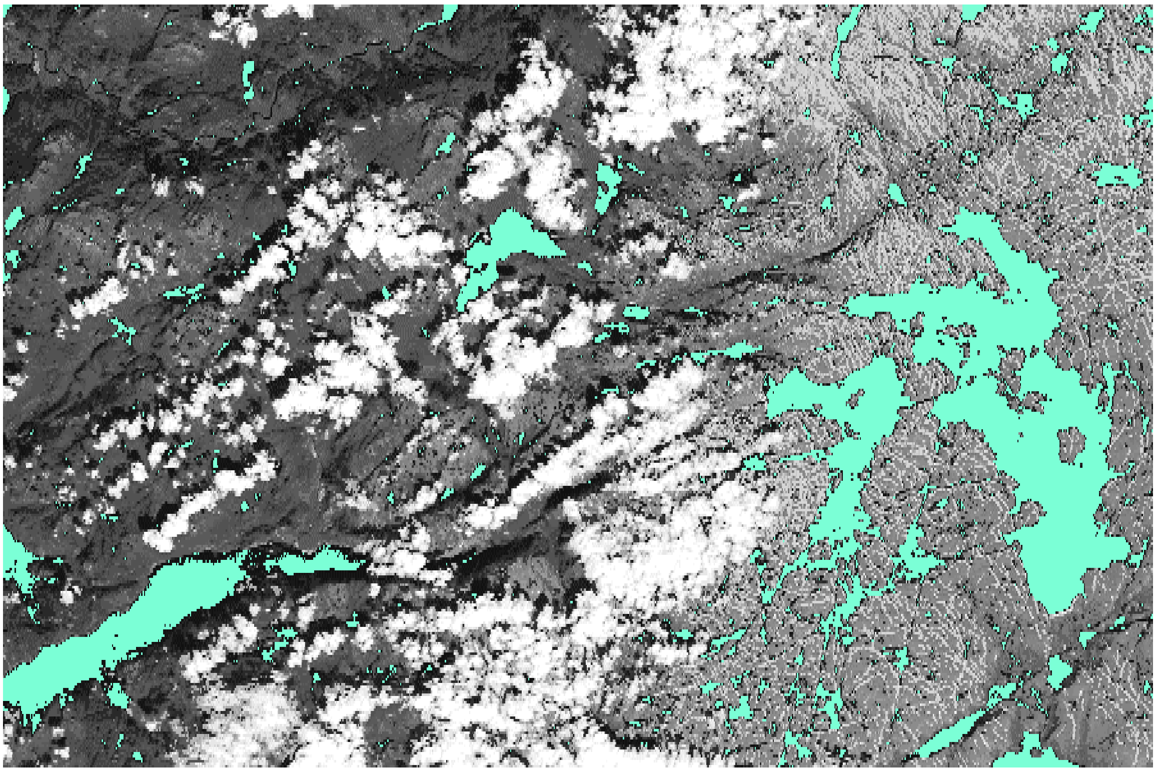


Figure 8.8 The result from running the ISODATA clustering routine on the Landsat-7 TM image. All TM bands were used to produce 25 clusters. Cluster number 1 is representing water surface, and is shown in aquamarine colour.

8.5 C-band DEM *voids* and surface cover type

The SRTM C-band *void data* in the Bykle test area (see image in Figure 8.2) is represented by 5673 pixels out of a total of 245241 pixels, which amounts to 2.3 %. These 5673 void pixels are distributed over three main surface categories in the following manner:

- Lake or dam = 150 pixels, or 0.06 %
- Sea or fjord = 581 pixels, or 0.24 %
- Land surface = 4942 pixels, or 2.0 %

Thus, if water bodies can be masked or represented as a separate layer in the SRTM DEM, the *void data* will only represent around 2.0 % of the land pixels in a hilly terrain like Bykle. This means that in an extreme terrain (like the fjord regions in West Norway), *most of the land areas* can in fact be mapped with a spaceborne InSAR system. Only a *small* portion of the area needs to be mapped by other means.

8.6 C-band DEM *voids* and sloping terrain

Although the C-band DEM *void data* represents a relatively small portion of the full data set, it is important to know what kind of terrain that may cause these voids. In theory, the *voids* are due to low InSAR coherence caused by geometric effects (layover or shadow), unwrapping errors (i.e. too steep slopes) or a very low SAR backscattering signal. The last point cannot be checked since no SRTM C-band SAR image was available from Bykle. However, the geometry effect can be investigated using the N50 reference DEM from Bykle. In this context, two products were derived from the N50 reference DEM: a terrain aspect map, and a terrain slope map. The terrain slope map is shown in Figure 8.9. Clearly, there are quite steep terrain slopes in some of the fjords.

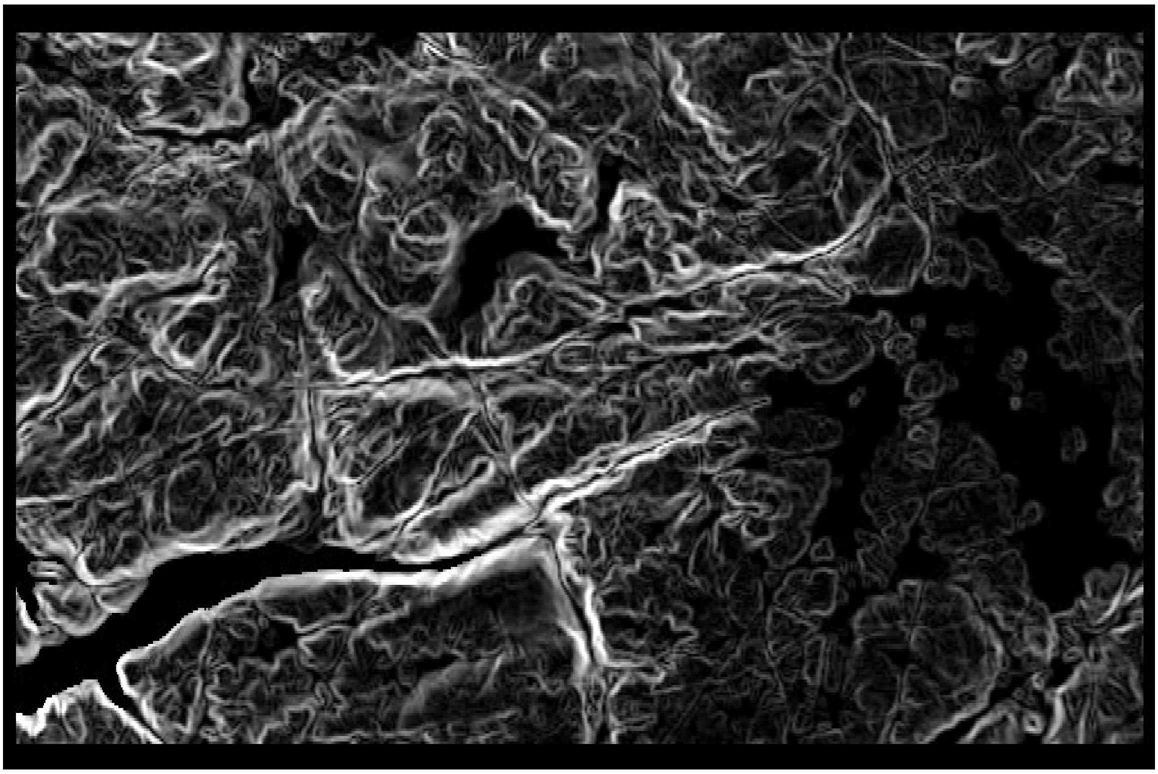


Figure 8.9 Terrain slope map obtained from the N50 reference DEM. Steeper slopes are represented with a brighter grey tone.

An analysis of the SRTM C-band *void data* are carried out by plotting the histograms for various terrain parameters: elevation height, slope, and aspect. The results are given in Figure 8.10. The top left histogram shows the distribution of all terrain points in the region (excluding water bodies). This shows an over-representation of elevation heights from 1050 m to 1100 m, which only reflects the special terrain at the Bykle test site. The other four histograms are produced from the criteria that the SRTM C-band DEM should contain *void data* at the pixel position under investigation. The upper right histogram shows that the C-band *void data* are in general distributed over the full range of elevation values, but with an emphasis on elevations below 1000 m. The histogram plot at the bottom is a combination of the two histograms in the middle. This combined histogram clearly shows that most *data voids* are present at places where the terrain slopes are between 20 and 60 degrees <u>and</u> where these slopes are <u>either</u> facing South (180 degrees aspect) <u>or</u> North (360 degrees aspect).

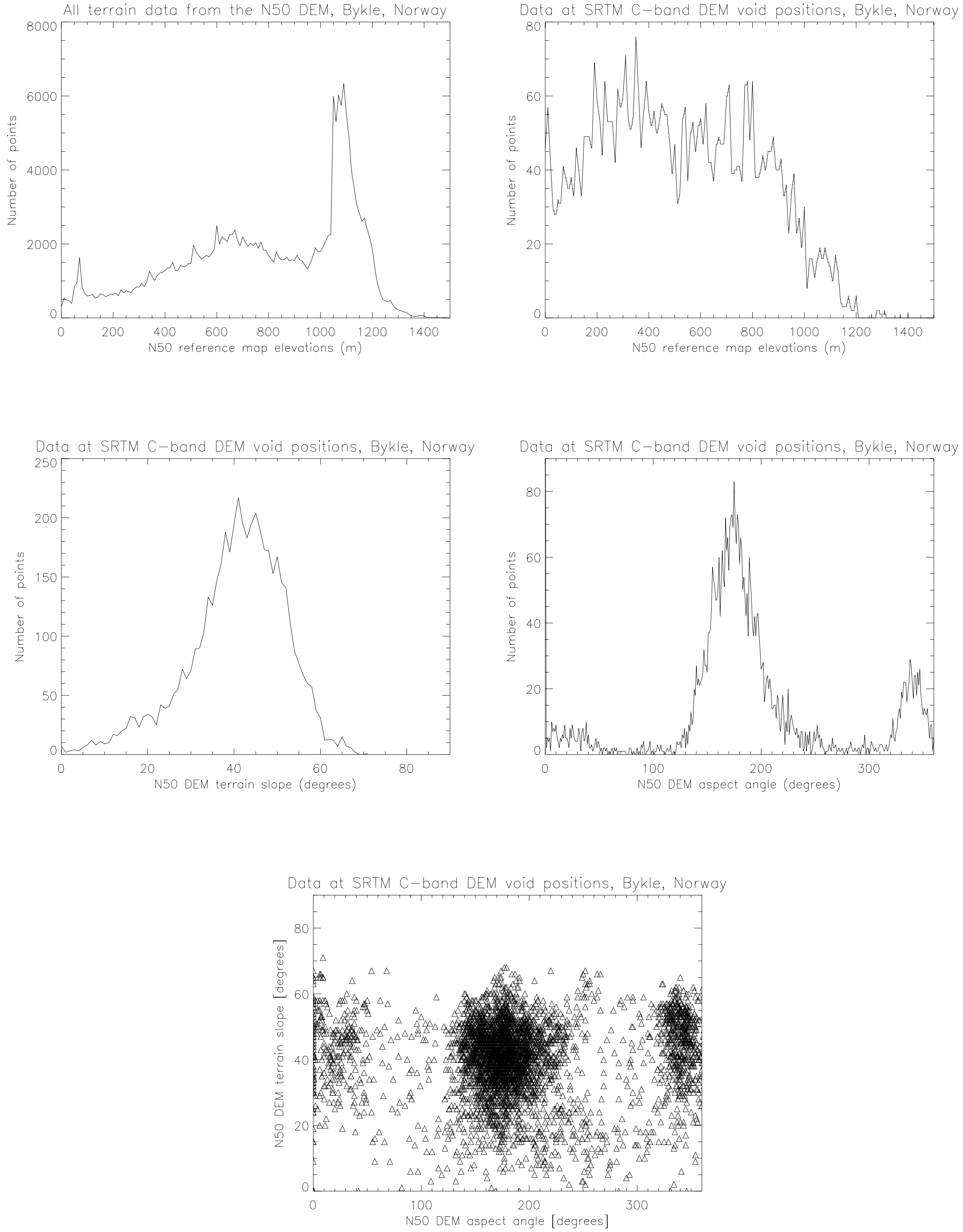


Figure 8.10 Histogram plots at the locations where the SRTM C-band DEM holds void data. The plot at the bottom is combining the results from the two histograms in the middle. Clearly, most data voids are present at places where the terrain slopes are between 20 and 60 degrees and where these slopes are either facing South (180 degrees aspect) or North (360 degrees aspect).

The SRTM C-band system operated with a look angle from 30-60 degrees. The characteristic layover and shadowing effects that often occur for SAR systems that are viewing areas with large terrain relief may normally be compensated for by means of ascending and descending pass. However, due to the high latitude of our test area, the Shuttle was only able to acquire the interferometric SAR data from more or less the same aspect angle, i.e. from the South (see also the SRTM X-band acquisition map in Figure 7.2). This was also the case for some areas at the Vestfold test site, but it is even more pronounced at the Bykle test site where there are deep fjords with mountains reaching up to more than 1200 m a.s.l. This is the main reason for why large SRTM DEM errors are located in areas of steep sloping terrain and where the aspect angle is around 180 and 360 degrees.

The SRTM C-band *void data* should be masked, corrected or substituted with elevation data from other sources before using the SRTM DEM in real life applications. Some of these *voids* have been corrected in the "finished" version of the SRTM C-band DEM now available from USGS [SRTM web page with download of finished C-band data, 2005]. It is outside the scope of this work to investigate any further the algorithms used to correct the *voids*, but the interested reader may refer to the many presentations at the SRTM Workshop held in USA in June 2005 [SRTM Workshop 2005].

8.7 Comparing the C-band *voids* with X-band HEM data

Another interesting matter is to compare the C-band *void data* with the X-band HEM data. In Figure 8.11, SRTM X-band HEM histograms are plotted from land surface areas (i.e. excluding water bodies). The two histograms at the top show the original HEM data from most of the Bykle test site (original to the left, and scaling the y-axis to the right).

The X-band HEM histogram in the lower plot in Figure 8.11 is restricted to SRTM C-band *void data* observed over land areas (i.e. the 4942 pixels mentioned in section 8.5). We can see that C-band *void data* are represented for HEM-values in the range from 2-100 m, but there seem to be an overrepresentation of HEM values in the range from 40-65 m. This top can also be spotted in the original HEM histogram (top left plot in Figure 8.11). In practise this means that the C-band *void data* indeed hold large errors, errors that for most of the *void data* are notified to more than 40 m in the X-band HEM estimate! This is confirmed by the statistical calculations performed in the next section.

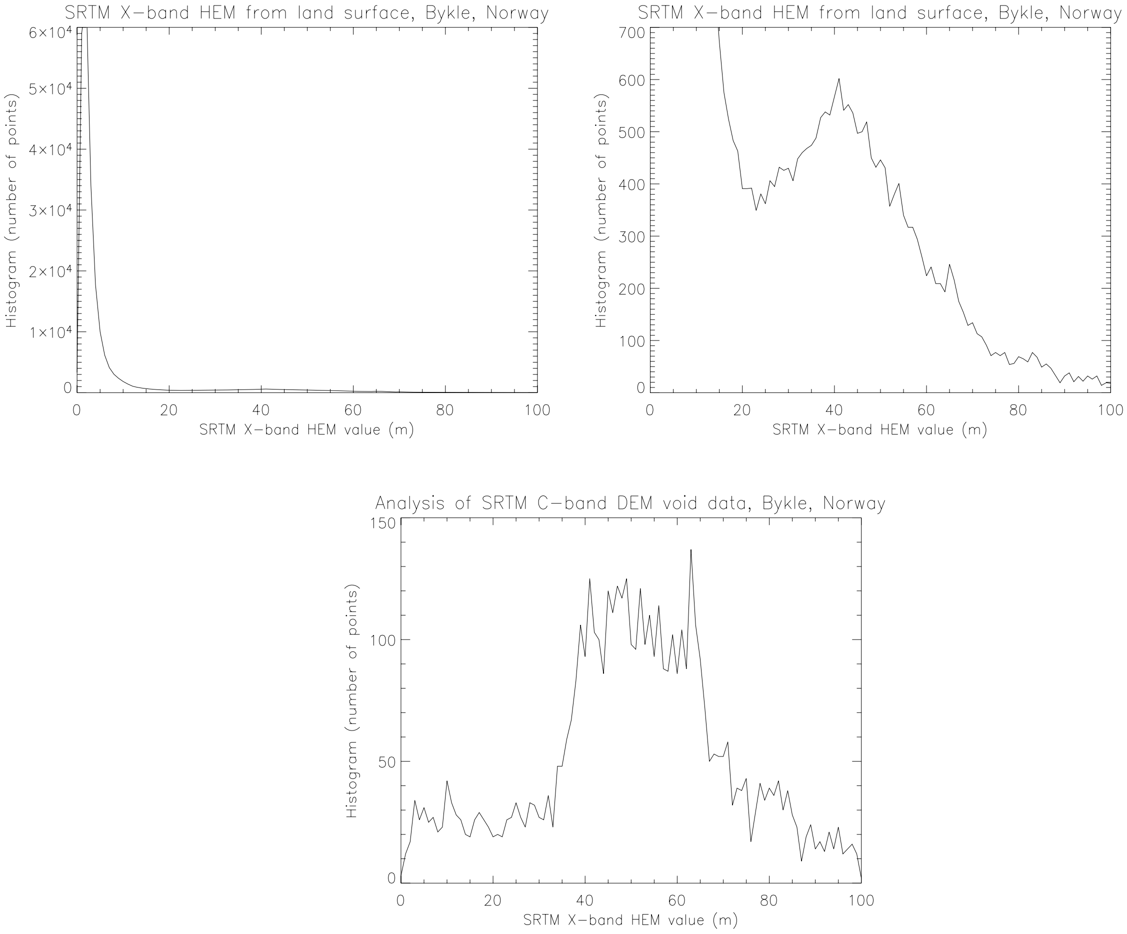


Figure 8.11 SRTM X-band HEM values plotted for land surface terrain (i.e. excluding void data over water bodies) from the Bykle test site in Norway. Original histogram plotted for all HEM values (top left). The same original histogram, but using another scaling on the y-axis (top right). HEM distribution under the restriction of SRTM C-band DEM void data (below).

8.8 Absolute elevation accuracy in mountainous terrain

The C-band and X-band SRTM DEMs are compared with the N50 reference DEM. The water body mask is used to ensure that only land pixels are evaluated. The *void data* are excluded from the statistical analysis of the C-band DEM. The X-band DEM is evaluated over all land pixels that fall within certain HEM boundaries (6 m, 30 m and 16 m). Results are given in Table 8.3.

The *mean difference* is estimated using equation *(7.2)* in chapter 7.7.4. The standard deviation, RMSE and minimum and maximum values are also obtained. The “90 m” (unedited) C-band DEM gives an overall RMSE of 7.3 m. This translates to +/- 12 m for a 90 % confidence level. Although this result is within the +/- 16 m level set by the SRTM specifications, it is slightly poorer than the result obtained from agricultural fields (an RMSE of 4.6 m with a 90 %

confidence level of +/- 6.5 m, see Table 7.9). The rugged terrain as well as inaccuracies in the N50 reference map may lead to the higher 90 % confidence level (up to +/- 12 m) for the Bykle test site.

The mean difference ("MEAN diff.") values in Table 8.3 are less than 1 m. This clearly indicates a good vertical calibration of the SRTM DEM products. The rough terrain, inaccuracies in the N50 DEM, or small uncertainties in the SRTM DEM calibration may cause the small vertical offset of +0.5 m and –0.6 m.

The "30 m" X-band DEM was evaluated for three different HEM boundaries. The HEM boundary was first adjusted until the +/- 12 m level was achieved. This is the same as for the C-band data. The HEM boundary was then 30 m. Now, let us compare the results from the C- and X-band statistics in Table 8.3. In order to obtain the same vertical accuracy, one has to include pixels from larger HEM values (up to 30 m), but still there will be fewer pixels evaluated (92.1 % for X-band as compared to 97.7 % for C-band). This shows:

1) The HEM values derived at DLR are quite conservative. In other words, we can accept a much higher HEM value than 6 m or 16 m in order to get the same result as with the C-band DEM.

2) The X-band data will have a larger spread of height values. The X-band DEM excludes many pixels that are accepted as valid elevation points in the C-band DEM. This is reflected in the smaller number of land pixels evaluated for the X-band data when the HEM values were set < 30 m.

When interpreting these results, one should also note that the C-band DEM probably is made out of 8-10 acquisitions, while the X-band DEM is a result of averaging over only 3-5 acquisitions in this region (see also explanation of Figure 8.6 in chapter 8.3). The larger number of acquisitions for the C-band data will in general lead to a smaller error standard deviation when evaluating the same pixels.

Ideally, the end user would like the DEM to contain no *void data*. Recently, the SRTM processing facilities and the international society have addressed how *void data* may be substituted with elevation data that is well within the error boundaries [SRTM Workshop, 2005]. Hopefully, the result of these studies is that new SRTM DEMs with no *void data* will be produced in the near future.

SRTM data	**Land pixels evaluated [%]**	**MEAN diff. [m]**	**STD diff. [m]**	**Min diff. [m]**	**Max diff. [m]**	**RMSE of difference [m]**	**90 % confidence level [m] (RMSE*1.649)**
C-DEM (no *void data* and no water)	97.7	0.5	7.3	-196	397	7.3	+/- 12.0
X-DEM where HEM < 30 m	92.1	-0.6	7.3	-122	214	7.3	+/- 12.0
X-DEM where HEM < 16 m	89.3	-0.8	6.0	-61	204	6.1	+/- 10.0
X-DEM where HEM < 6 m	76.2	-1.2	4.8	-35	168	5.0	+/- 8.2

Table 8.3 *Statistics after analysing two SRTM DEM products with respect to the N50 reference DEM. Note that sea, fjord and lake pixels are masked prior to the analysis.*

9 CONCLUSIONS

The SRTM C-band DEM ("90 m" unedited data) and X-band DEM ("30 m" data) are evaluated from two test sites in Norway. Both DEM products contain many details not seen in commonly used digital maps of the same scale. Such elevation details may originate from buildings, small streams cutting through fields, forest height variations, or roads/open patches within a forest.

The absolute horizontal accuracy of the SRTM DEM products is estimated to better than 1/5 of a pixel. This is well within the +/- 20 m and +/- 60 m specifications for the "30 m" and "90 m" products respectively. The relative vertical accuracy was found to be just within the specifications of +/- 6 m for the X-band system and +/- 10 m for the C-band system.

The SRTM DEM products are calibrated by the interferometric SAR processing facilities in the US and Germany. However, the DEMs may still hold a small vertical offset. Investigating agricultural fields in the Vestfold test area showed that the SRTM X-band and C-band DEM products had to be corrected by +1.0 m and –3.3 m respectively. However, one should notice that without this correction, the absolute vertical accuracy would still be within the specified +/- 16 m (90 % confidence level) for most surface cover types.

After correcting for the small vertical offset, agricultural fields gave an absolute vertical accuracy of 5.2 m and 6.5 m (90 % confidence level) for the X-band and C-band DEMs respectively. The corresponding RMSE values were 3.4 m and 4.6 m.

The SRTM system will refer its elevations with respect to the *reflective surface* computed from the interferometric SAR returns from the Earth features. An SRTM DEM may therefore be referred to as a *digital surface map* (DSM) rather than a digital terrain map (DTM). As a result, the SRTM DEMs will include cultural features (man-made) and vegetation canopy elevations. Results show that dense forest areas will be mapped with an elevation 10-17 m above the true ground, which is approximately 1/2 to 2/3 of the true tree height. If the required accuracy of a DEM is +/- 16 m referring to the *ground*, then the SRTM DEMs seem to be sufficiently accurate also over many forested regions, and can therefore be used as is. However, if accurate *ground* elevation maps are required, the forest areas should be excluded from the SRTM DEM using other sources (e.g. GIS or optical satellite images), or treated separately.

The SRTM DEMs are used to estimate the total volume of rock removed from several large gravel pits in Vestfold.

An average elevation up to 5 m above the ground was estimated in some city areas. This indicates building heights within the area. It is believed that this number will vary according to the density of the man-made structures and the spatial resolution of the SAR system. Results from an airport show that large building structures can be mapped down towards one-meter accuracy in elevation.

The SRTM DEM has a higher vertical accuracy than the commonly used 1:50 000 DEM (N50) in non-forest areas. In fact, the SRTM DEM may be used to pinpoint particularly large elevation errors that still are present in the 1:5000 digital maps (N5) also delivered by the Norwegian Mapping Authority.

Hydroelectric dams may very well be used to calibrate the SRTM DEMs to sub-meter accuracies. Best results are obtained when the SAR backscatter from the water surface is relatively high due to strong wind conditions or a rough ice-covered surface.

The SRTM interferometric SAR processing system is able to automatically flag particularly large elevation errors. These areas are flagged in the SRTM C-band DEM products as *void data*, and as a separate error file in the case of X-band data. It is clearly an advantage that SRTM DEM pixels with particularly large errors, due to radar geometry and radar system limitations, are flagged when obtaining the SRTM data from the agency. Results show that only a minor portion of the SRTM data from Vestfold had particularly large errors in this respect. Even the extreme mountainous terrain in the Bykle region in Norway would only flag 2 % of the land pixels as no-data. The remaining SRTM DEM pixels in the mountainous terrain gave an absolute vertical accuracy that was better than 12 m (90 % confidence level). In contrast to the Norwegian test areas, it is believed that a better result could be obtained from mountainous terrain at lower latitudes when both ascending and descending SRTM passes can be used to build up the final SRTM DEM.

10 RECOMMENDATIONS

The C-band and the X-band SRTM DEMs are within the DTED Level-2 specifications in areas not holding extreme slopes. The SRTM DEMs are therefore recommended for any mapping application that needs elevation maps in the scale 1:50 000, and that are not restricted to ground level heights in dense forest areas. Some specific land mapping applications may be:

- substituting the old 1:50 000 DEMs at many places
- correcting/updating old maps
- geocoding optical and radar satellite images
- watershed analysis
- flight simulators
- line-of-sight analysis for military applications or mobile communication systems

In the context of the second point above, the Norwegian Mapping Authority can use SRTM DEMs to correct errors in the existing 1:50 000 and 1:5000 DEMs.

High-resolution DEMs can be produced from spaceborne InSAR platforms. These DEMs can be used on a regular basis to estimate stamp mill production as well as other man-made activities in and area.

SRTM DEMs should not in *general* be used to map building heights, but may in some cases give interesting measurements from certain objects.

Dense forest stands may model the SRTM DEM to measure elevations that are 10-17 m above the true ground.

The *unedited* SRTM C-band DEM studied here will hold numerous *void data*. These no-data pixels should be substituted by real elevation values so that the end user can treat the SRTM DEM file as any other DEM. The SRTM DEM processing facility will need to develop good algorithms for filling in the *void data* in a consistent manner before delivering the “finished” SRTM product. This challenge was thoroughly addressed at the SRTM Workshop held in USA in June 2005 [SRTM Workshop 2005]. The next generation SRTM products will benefit from these developments.

The SRTM C-band DEM file should be accompanied by a separate file indicating the estimated height errors (similarly to the HEM-file produced by DLR in Germany) derived from the interferometric processing and mapping geometry.

Water level recordings from frozen lakes or hydroelectric dams can very well be used to calibrate the SRTM DEM to sub-meter accuracy.

Water boundaries and water elevations could be given as a separate layer or file. The end user can then substitute this information into the SRTM DEM as needed.

For future interferometric SAR missions, it is recommended to use polar orbiting satellites in order to also map latitudes above +60 degrees North and below –56 degrees South. One should also use many satellite passes (up to 10) from both ascending and descending orbits when building up the final DEM product. In this manner it is possible to obtain elevation errors down towards 1 m, and with minimal no-data areas caused by steep slopes in mountainous regions. It should then be possible to regularly monitor the water level of hydroelectric dams all around the World with sub-meter accuracies.

References

Allen, C. T., “Review Article: Interferometric Synthetic Aperture Radar”, *IEEE Geoscience and Remote Sensing Society Newsletter*, September 1995.

Bamler, R., “Digital terrain models from radar interferometry”, *Photogrammetric Week ‘97*, pp. 93-105, Wichmann Verlag, Heidelberg, Germany, 1997.

Bamler, R., “The SRTM mission: A world-wide 30 m resolution DEM from SAR interferometry in 11 days”, *Photogrammetric Week ‘99*, pp. 145-154, Wichmann Verlag, Heidelberg, Germany, 1999.

Bjørke, T., “Building heights in Horten Harbour”, Personal communication, June 2005.

DTED Specification, “Performance Specification of the Digital Terrain Elevation Data (DTED)”, MIL-PRF-89020B, 23 May 2000.

Engeset, R. V., ”NVE water level recordings from dams in Bykle, Norway”, Personal communication, November 2004.

Ferretti, A., C. Prati, F. Rocca and A. Monti Guarnieri, “Multibaseline SAR interferometry for automatic DEM reconstruction”, *3rd ERS Workshop*, http://earth.esa.int/symposia/ers97/, Florence, Italy, 1997.

Gatelli, F., A. M. Guarnieri, F. Parizzi, P. Pasquali, C. Prati and F. Rocca, “The wavenumber shift in SAR interferometry”, *IEEE Trans. Geosci. Remote Sens.*, Vol. 32, No. 4, pp. 855–865, 1994.

Gens, R., and J. L. Van Genderen, “Review Article: SAR interferometry – issues, techniques, applications”, *Int. J. Remote Sensing*, Vol. 17, No. 10, pp. 1803-1835, 1996.

Kellndorfer, J. M., W. Walker, L. Pierce, C. Dobson, J. A. Fites, C. Hunsaker J. Vona and M. Clutter, “Vegetation height estimation from Shuttle Radar Topography Mission and National Elevation Datasets”, Remote Sensing of Environment, Vol. 93, No. 3, pp. 339-358, 2004a.

Kellndorfer, J. M., W. S. Walker, M. C. Dobson, J. Vona and M. Clutter, “Vegetation height derivation from Shuttle Radar Topography Mission data in southeast Georgia USA”, Proceedings of IEEE International Geoscience and Remote Sensing Symposium (IGARSS), VII, 4512-4515, Anchorage, Alaska, 20-24 September, 2004b.

Li, F., and R. M. Goldstein, “Studies of multibaseline spaceborne interferometric synthetic aperture radars”, *IEEE Trans. Geosci. Remote Sens.*, Vol. 28, No. 4, pp. 88-97, 1990.

Marschalk, U., A. Roth, M. Eineder and S. Suchandt, “Comparison of DEMs derived from SRTM/X- and C-band”, *Proceedings of IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, pp. 4531-4534, Alaska, 2004.

Massonnet, D., M. Rossi, C. Carmona, F. Adragna, G. Peltzer, K. Feigl, and T. Rabaute, “The displacement field of the Landers earthquake mapped by radar interferometry”, *Nature*, Vol. 364, No. 6433, pp. 138–142, 1993.

Massonnet, D., and K. Feigl, “Radar interferometry and its application to changes in the Earth’s surface”, *Reviews of Geophysics*, Vol. 36, No. 4, pp. 441-500, 1998.

NASA, Instrument Panel Report: SAR Synthetic Aperture Radar Earth Observation System, Vol IIf, Earth Science and Application Division, NASA Headquarters, Washington, DC, 233 pages, 1989.

Olaisen, G. M., “Rapport for GPS-måling”, (Report showing GPS-measurements of radar corner reflector positions within Vestfold County), Statens Kartverk Vestfold, 2000.

Rabus, B., M. Eineder, A. Roth, and R. Bambler, “The shuttle radar topography mission – a new class of digital elevation models acquired by spaceborne radar”, *ISPRS Journal of Photogrammetry & Remote Sensing*, Vol. 57, pp. 241-262, February 2003.

Rignot, E. J. M., and J. J. van Zyl, “Change detection techniques for ERS–1 SAR data”, *IEEE Trans. Geosci. Remote Sens.*, Vol. 31, No. 4, pp. 896–906, 1993.

Rosen, P. A., S. Hensley, I. R. Joughin, F. K. Li, S. N. Madsen, E. Rodriguez and R. M. Goldstein, ”Synthetic Aperture Radar Interferometry”, *Proceedings of the IEEE*, Vol. 88, No. 3, pp. 333-382, 2000.

Rosen, P. A., S. Hensley, E. Gurrola, F. Rogez, S. Chan, J. Martin and E. Rodriguez, “SRTM C-band topographic data: Quality assessment and calibration activities”, *IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, pp. 739-741, Sydney, Australia, 2001.

Sagstuen, J., “Analysis of SRTM elevation data covering forest and open land areas in Vestfold”, Master Thesis (- in Norwegian), Dept. of Mathematical Sciences and Technology at the Norwegian University of Life Sciences (former: Agricultural University of Norway, Department of Mapping Sciences), June 2003.

SRTM main web page at JPL, URL: http://www2.jpl.nasa.gov/srtm/, NASA’s Jet Propulsion Laboratory, California, USA, (last date accessed: 25 June 2005).

SRTM web page at JPL showing data products, URL: http://www2.jpl.nasa.gov/srtm/cbanddataproducts.html, NASA’s Jet Propulsion Laboratory, California, USA, (last date accessed: 25 June 2005).

SRTM web page showing overview of data products at USGS, URL: http://srtm.usgs.gov/index.html, Overview of SRTM C-band DEM data products, USGS, (last date accessed: 25 June 2005).

SRTM main web page at DLR, URL: http://www.dlr.de/srtm/, German Aerospace Center, Germany, (last date accessed: 25 June 2005).

SRTM web page with download of finished C-band data, URL: http://edc.usgs.gov/products/elevation.html, Download of “30 m” and “90 m “ finished SRTM C-band DEM data, USGS, EROS Data Center Products, (last date accessed: 25 June 2005).

SRTM web page for download of seamless USGS data, URL: http://seamless.usgs.gov/, Download of seamless SRTM C-band data, USGS, EROS Data Center (last date accessed: 25 June 2005).

SRTM web page with download of scientific C-band data, URL: ftp://e0mss21u.ecs.nasa.gov/srtm/, Free download of scientific “90 m “ *unedited* SRTM C-band DEM data, NASA, USA, (last date accessed: 25 June 2005).

SRTM Workshop, “The Shuttle Radar Topography Mission – Data Validation and Applications”, Reston, Virginia, USA, 14-16 June 2005. URL: http://edc.usgs.gov/conferences/SRTM/

Wegmüller, U., and C. Werner, “Retrieval of vegetation parameters with SAR interferometry”, *IEEE Trans. Geosci. Remote Sens.*, Vol. 35, No. 1, pp. 18–24, 1997.

Weydahl, D. J., “Analysis of ERS SAR coherence images acquired over vegetated areas and urban features”, *Int. J. Remote Sensing*, Vol. 22, No. 14, pp. 2811-2830, 2001a.

Weydahl, D. J., “Analysis of ERS tandem SAR coherence from glaciers, valleys and fjord ice on Svalbard”, *IEEE Trans. Geosci. Remote Sens.*, Vol. 39, No. 9, pp. 2029-2039, 2001b.

Weydahl, D. J., J. Sagstuen, Ø. Dick, H. Rønning and L. Hansen, “Analysis of X-SAR SRTM Elevation Data to Estimate Surface Cover Heights over Land Areas”, *Proceedings of IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, pp. 112 – 114, Toulouse, France, 21-25 July 2003.

Weydahl, D. J., “Analysis of SRTM elevation data over forested and agricultural land areas in Norway”, *5th European Conference on Synthetic Aperture Radar (EUSAR)*, Ulm, Germany, Ulm, 25-27 May 2004.

WGS 84 Earth Gravitational Model: URL: http://earth-info.nima.mil/GandG/wgs84/gravitymod/index.htm, National Geospatial-Intelligence Agency (NGA), Geospatial Sciences Division, USA, (last date accessed: 25 June 2005).

Zebker, H. A., and R. M. Goldstein, “Topographic mapping from interferometric synthetic aperture radar observations”, *Journal of Geophysical Research*, 91(B5), pp. 4993-4999, 1986.

Zebker, H. A., and J. Villasenor, “Decorrelation in interferometry radar echoes”, *IEEE Trans. Geosci. Remote Sens.*, Vol. 30, pp. 950-959, 1992.

APPENDIX

A.1 Abbreviations

AO	Announcement of Opportunity
AODA	Attitude and Orbit Determination Avionics
DEM	Digital Elevation Model
DLR	German Aerospace Center
DSM	Digital Surface Map
DTED	Digital Terrain Elevation Data
DTM	Digital Terrain Map
EGM	Earth Gravitational Model
ENVISAT	ESA’s Environmental Remote Sensing Satellite
ERS	European Remote sensing Satellite
ESA	European Space Agency
FFT	Fast Fourier Transform
FMGT	Norwegian Military Geographic Service
GCP	Ground Control Point
GIM	Geocoded Incidence angle Mask
GIS	Geographic Information System
GTC	Geocoded Terrain-Corrected
HEM	Height Error Map
InSAR	Interferometric Synthetic Aperture Radar
JPL	Jet Propulsion Laboratory
NASA	National Aeronautics and Space Administration
NGA	National Geospatial-Intelligence Agency
NVE	Norwegian Water Resources & Energy Directorate
PI	Principal Investigator
RADARSAT	The Canadian Radar Remote Sensing Satellite
RMSE	Root Mean Square Error
ROI	Region Of Interest
SAR	Synthetic Aperture Radar
SIR-C	Spaceborne Imaging Radar-C
SRTM	Shuttle Radar Topography Mission
USGS	United States Geological Survey
UTM	Universal Transverse Mercator Projection
WGS84	World Geodetic System 1984

A.2 Corrections of the N5 vector data

Correction of 80 elements in the N5 vector data set. The data set covers part of Vestfold County in Norway. Norwegian Mapping Authority delivered this vector data set in February 2004. Some comments to the table below:

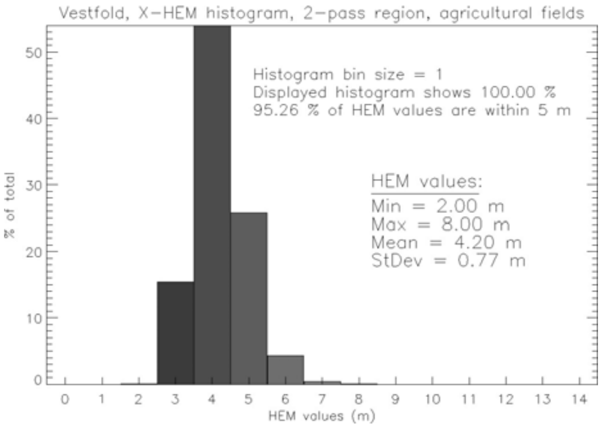
- “Cell” is referring to the sub-division of the entire area that is used for practical matters in the present GIS system.
- “Hpunkt” is height point.
- “Hkote” is elevation contour.
- “VBASE” is height point found in the road database.

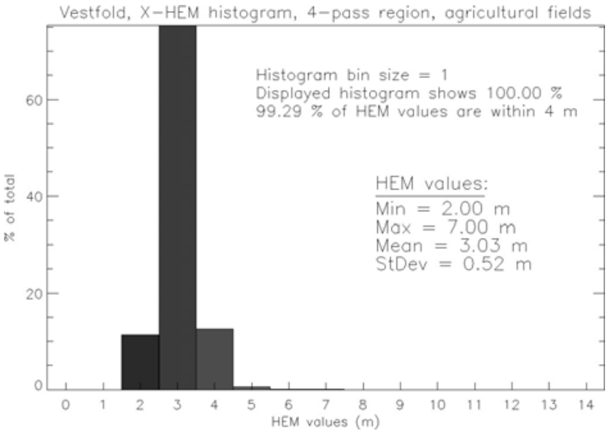
Cell	Type	UTM (X)	UTM (Y)	HOYDEL_ / HOYDEP_	ID	Length [m]	Height [m]	Action performed, Comment	
1		5 44 676	65 80 890	51837	8120	-	436	Excluded	Closest contour is 535 m
1	Hpunkt	5 50 026	65 85 466	51250	3607	-	258.2	Excluded	Closest contour is 280-285 m
1	Hpunkt	5 49 500	65 77 422	51120	3477	-	76.1	Excluded	Closest contour is 175 m
1	Hpunkt	5 54 035	65 88 109	51589	3946	-	149.8	Excluded	Closest contour is 190 m
1	Hpunkt	5 53 808	65 85 830	51466	3823	-	12.1	Excluded	Closest contour is 120 m
2	Hpunkt	5 55 288	65 79 329	51439	3796	-	226.5	Excluded	Closest contour is 325 m
2	Hpunkt	5 63 359	65 87 947	46300	15613	-	259	Excluded	Closest contour is 155 m
2	Hpunkt	5 65 267	65 87 934	46322	15635	-	106	Excluded	Closest contour is 155 m
2	Hkote	5 54 577	65 89 624	237577	3011	270.37	215	245	Part of contour
2	Hkote	5 55 857	65 89 536	237457	2891	35.14	50	75	Part of contour
2	Hkote	5 56 484	65 83 642	238385	4397	73.57	205	230	Top-contour
2	Hkote	5 58 894	65 79 063	178219	2510	833.76	260	185	A full contour
2	Hkote	5 59 247	65 82 651	184711	9088	44.64	265	295	Part of contour
2	Hkote	5 57 200	65 83 246	238329	4341	111.58	285	310	A full contour
2	Hkote	5 58 148	65 89 462	235854	1288	4.60	140	Excluded	Double up: other contour is OK
2	Hkote	5 61 326	65 86 034	173026	15771	146.29	300	275	A full contour
2	Hkote	5 61 320	65 86 183	173025	15770	98.85	300	275	-
2	Hkote	5 61 431	65 86 701	173028	15773	83.02	300	275	-
2	Hkote	5 61 428	65 86 743	173027	15772	96.15	300	275	-
2	Hkote	5 61 535	65 86 567	173048	15793	30.10	290	285	Top-contour
2	Hkote	5 63 479	65 87 552	173688	16481	102.02	120	130	Part of contour
2	Hkote	5 63 479	65 87 542	173687	16480	85.26	115	135	Part of contour
2	Hkote	5 64 488	65 85 097	173372	16141	197.68	70	80	A full contour
2	Hkote	5 64 565	65 85 145	173373	16142	93.94	70	80	Part of contour

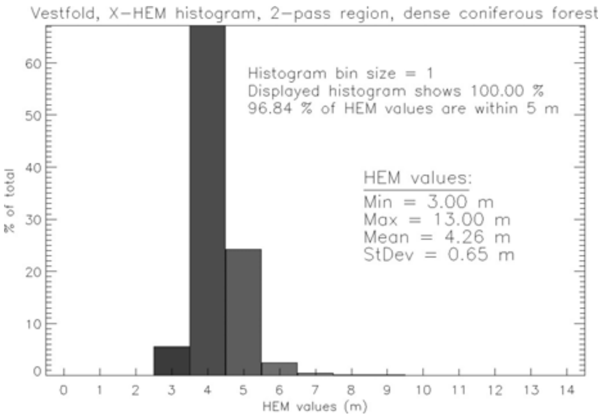
Cell	Type	UTM (X)	UTM (Y)	HOYDEL_ / HOYDEP_	ID	Length [m]	Height [m]	Action performed, Comment	
2	Hkote	5 61 190	65 83 835	173289	16034	3943.50	395	295	Part of longer contour
2	Hkote	5 61 190	65 83 835	184732	9109	966.78	395	295	Part of longer contour
2	Hkote	5 61 190	65 83 835	173290	16035	118.61	395	295	Part of longer contour
2	Hkote	5 61 190	65 83 835	184733	9110	1070.67	395	295	Part of longer contour
2	Hkote	5 61 246	65 82 811	184597	8966	678.49	290	390	-
2	Hkote	5 61 246	65 82 811	184598	8967	596.37	295	395	-
2	Hkote	5 61 246	65 82 900	173322	16091	1785.11	360	335	Part of contour, norhting
2	Hkote	5 61 246	65 82 900	173263	16008	1525.86	365	340	Part of contour, northing
2	Hkote	5 61 246	65 82 900	173264	16009	1493.07	370	345	Part of contour, northing
3	Hpunkt	5 67 154	65 84 910	46673	18051	-	126.2	Excluded	-
3	Hpunkt	5 67 171	65 80 917	46433	17811	-	114	Excluded	Closest contour is 140 m
3	Hpunkt	5 67 191	65 78 836	48135	12925	-	148	Excluded	Closest contour is 180 m
3	Hpunkt	5 70 809	65 77 100	47013	18391	-	147.3	Excluded	Closest contour is 170 m
3	Hpunkt	5 68 964	65 93 139	45652	5427	-	298	Excluded	Closest contour is 200 m
3	Hpunkt	5 72 863	65 87 843	45754	5529	-	82	Excluded	Closest contour is 90 m
3	Hpunkt	5 75 046	65 79 495	46839	18217	-	57.6	Excluded	Closest contour is 65 m
3	Hpunkt	5 75 368	65 81 547	45879	5654	-	62.5	Excluded	Closest contour is 90 m
3	Hpunkt	5 75 157	65 82 965	45852	5627	-	34.5	Excluded	Closest contour is 90 m
3	Hkote	5 66 208	65 79 423	188441	12880	66.80	110	125	Top-contour
4	Hpunkt	5 47 477	65 75 518	51138	3495	-	365.4	Excluded	Closest contour is 395 m
4	Hpunkt	5 50 083	65 65 259	14351	116727	-	869	Excluded	Closest contour is 80 m
4	Hkote	-	-	140114	111880	407.95	235	335	-
5	Hpunkt	5 61 691	65 66 773	48159	13322	-	139	239	Wrong in paper version!
5	Hpunkt	-	-	48332	15991	-	299	199	Wrong in paper version!
5	Hpunkt	5 62 663	65 69 905	48322	15186	-	248.5	148.5	Closest contour is 145 m
5	Hkote	5 58 940	65 66 931	194799	19747	109.65	205	230	Top-contour
5	Hkote	5 59 157	65 66 918	194798	19746	128.52	180	170	-
5	Hkote	5 57 794	65 69 483	177126	1351	355.25	295	190	Checked against paper version
5	Hkote	-	-	177104	1329	47.29	105	130	-
5	Hkote	5 63 158	65 71 050	190211	14807	65.04	135	160	-
5	Hkote	5 63 906	65 76 559	192002	16688	2279.45	250	225	Contour in between other contours
6	Hkote	5 68 480	65 69 445	199692	3883	590.43	75	50	Nearly top-contour
6	Hkote	5 67 280	65 65 325	197913	2075	58.85	80	110	Top-contour
6	Hkote	5 69 130	65 73 035	209604	14031	299.97	55	70	Andebu
6	Hkote	5 69 130	65 73 035	199179	3347	71.37	65	70	Andebu
6	Hkote	5 69 130	65 73 035	208951	13378	50.93	55	70	Andebu

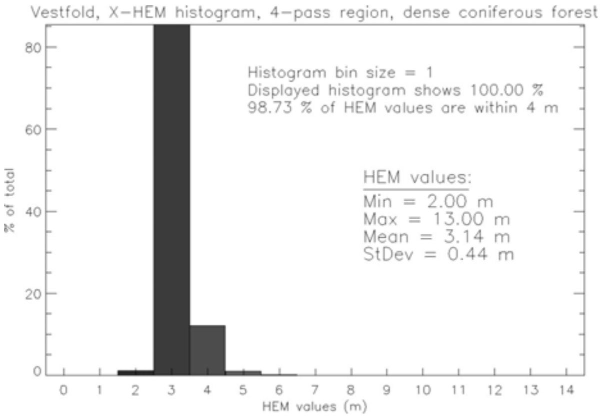
Cell	Type	UTM (X)	UTM (Y)	HOYDEL_ / HOYDEP_	ID	Length [m]	Height [m]	Action performed, Comment	
6	Hkote	5 69 130	65 73 035	199178	3346	35.13	65	70	Andebu
6	Hkote	5 69 800	65 75 740	200262	4453	201.81	130	110	-
6	Hkote	5 71 995	65 75 745	173736	16529	32.69	50	25	-
6	Hkote	5 72 843	65 72 718	204780	9084	34.86	90	65	Top-contour divided in two
6	Hkote	5 72 843	65 72 718	204894	9198	9.89	90	65	Top-contour divided in two
6	Hkote	5 72 505	65 71 860	204781	9085	290.67	90	65	Full top-contour
6	Hkote	5 72 542	65 68 559	212274	16775	9.98	60	70	Part of contour
6	Hkote	5 74 755	65 58 247	23094	8811	56.40	65	55	-
6	Hkote	5 74 649	65 58 831	202210	6427	167.32	5	30	Part of contour
6	Vbase	5 69 630	65 61 190	19024	19024	-	11	Excluded	Other points are approx. 110 m
6	Vbase	5 73 411	65 66 244	66731	66731	-	60	Excluded	Other points are approx. 65 m
7	Hpunkt	5 48 213	65 44 354	23378	138329	-	80.88	Excluded	Should have been between 25-30 m
7	Hpunkt	5 49 598	65 52 769	12549	101122	-	152	Excluded	Should have been a bit above 185 m
7	Hpunkt	-	-	12531	101104	-	168.5	Excluded	Should have been a bit above 185 m
8	Hpunkt	5 54 843	65 50 723	12872	104222	-	167.5	Excluded	Should have been a bit above 200 m
8	Hkote	5 63 393	65 55 114	51671	-	203.10	55	70	-
8	Hkote	5 61 638	65 47 683	43836	-	65.05	530	55	-
9	Hkote	5 65 829	65 57 370	31612	-	172.19	85	45	-
9	Hkote	-	-	31609	-	228.41	85	45	-
9	Vbase	5 67 634	65 56 165	19790	-	-	0.6	Excluded	Should have been around 62 m

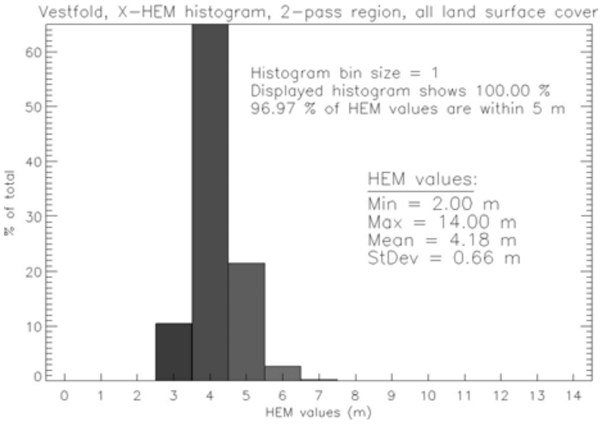
A.3 X-band HEM histograms, Vestfold

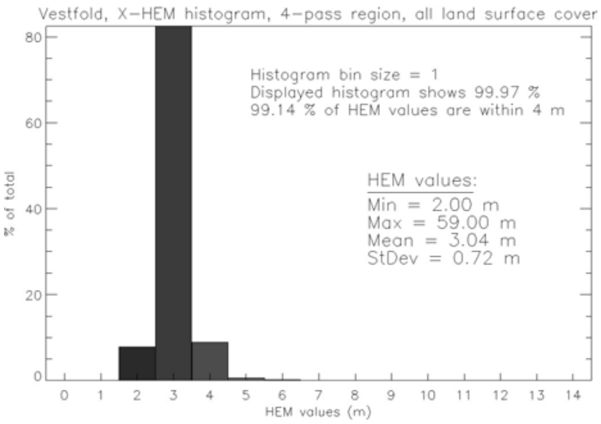












A.4 X-band DEM statistics at certain HEM values, Vestfold

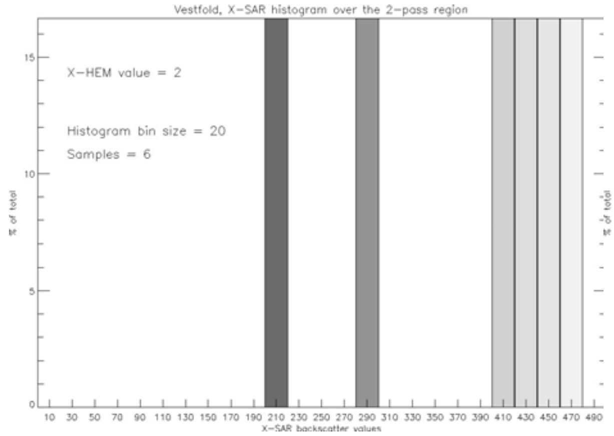
HEM value in 2-pass region	**RMSE (m)**	**Mean diff. (m)**	**St.Dev. (m)**	**Min. (m)**	**Max. (m)**
2	No samples available				
3	2.40	-0.88	2.23	-8.18	12.10
4	3.31	-0.26	3.30	-10.81	15.04
5	3.58	-0.90	3.47	-11.78	-14.62
6	3.83	-1.09	3.68	-11.79	12.83

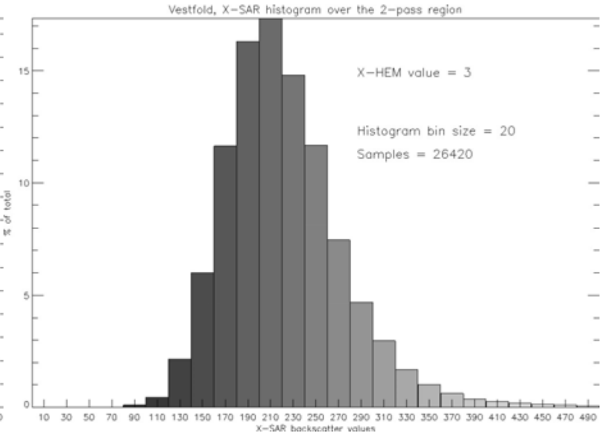
Table 1: SRTM X-band DEM statistics for certain HEM values over agricultural fields in the defined 2-pass region in Vestfold. The N5 map is used as the reference.

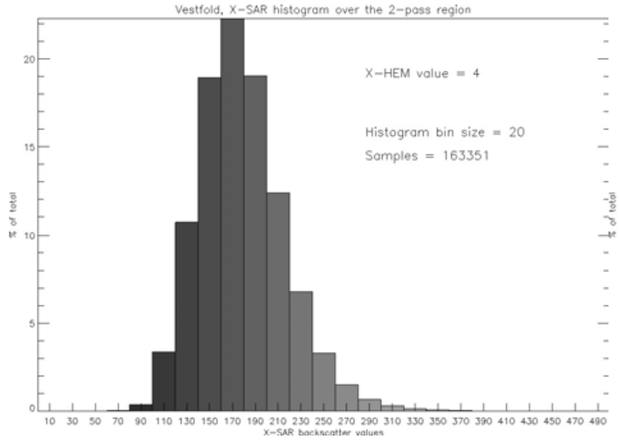
HEM value in 4-pass region	**RMSE (m)**	**Mean diff. (m)**	**St.Dev. (m)**	**Min. (m)**	**Max. (m)**
2	3.03	-2.37	1.89	-12.82	8.71
3	3.41	-0.84	3.31	-17.22	19.82
4	4.36	-1.17	4.20	-14.09	21.15
5	Larger uncertainties due to < 100 samples				
6	Larger uncertainties due to < 100 samples				

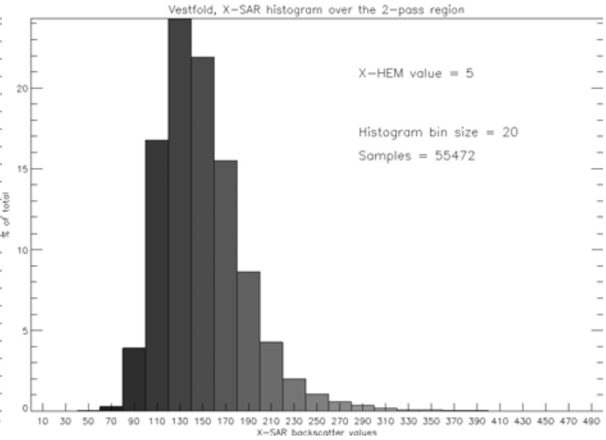
Table 2: SRTM X-band DEM statistics for certain HEM values over agricultural fields in the defined 4-pass region Vestfold. The N5 map is used as the reference.

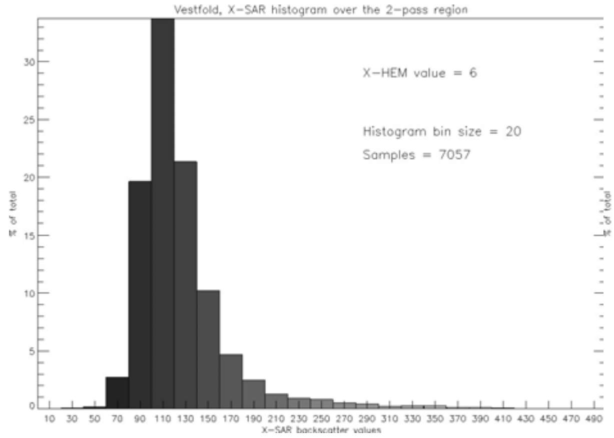
A.5 X-SAR backscatter histograms over the 2-pass region, Vestfold

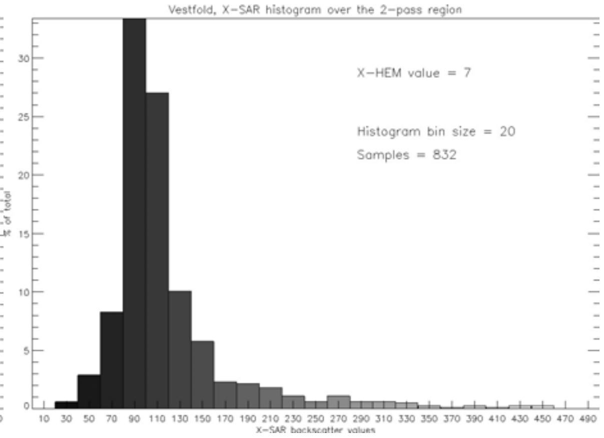


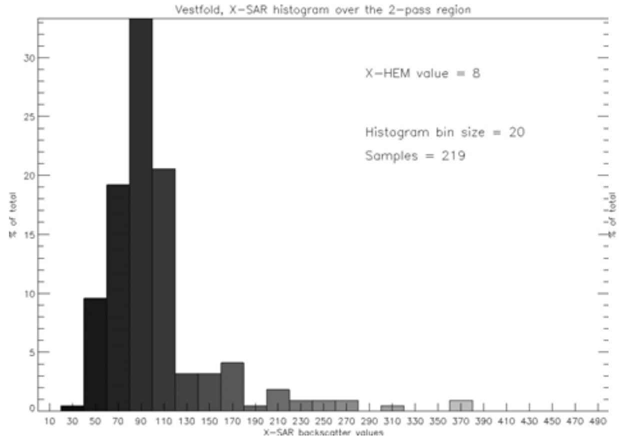


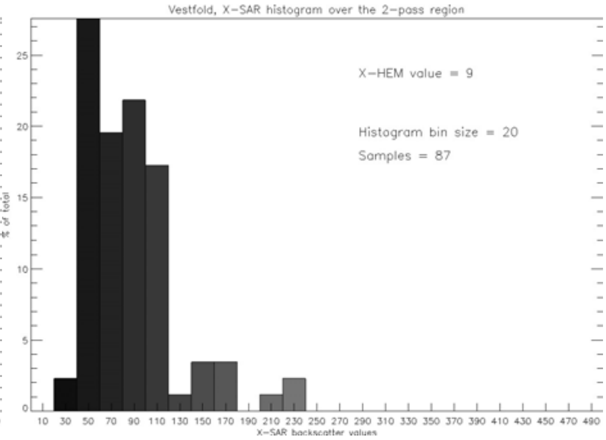












A.6 X-SAR backscatter histograms over the 4-pass region, Vestfold