EU-DEM Statistical Validation

Report

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Executive summary

The Geoscience Laser Altimeter System (GLAS) instrument onboard the Ice, Cloud, and land Elevation Satellite (ICESat) provides a globally distributed elevation data set that is well-suited to independently evaluate the accuracy of continent-wide digital elevation models (DEMs), such as EU-DEM.

EU-DEM is a hybrid product based mainly on SRTM and ASTER GDEM but also public available Russian topographic maps. The EU-DEM statistical validation documents a relatively unbiased (-0.56 meters) overall vertical accuracy of 2.9 meters RMSE, which is fully within the contractual specification of 7m RMSE. Evaluation of RMSE values as per country revealed higher RMSE values for the Nordic countries of Iceland (RMSE=9.41 m), Norway (RMSE=5.75 m) and Sweden (RMSE=7.41 m), which can be explained by the absence of SRTM data north of 60^{o}N.

Further, investigations of EU-DEM elevation accuracy documented increasing elevation biases and variability in areas of variable topography and ground cover. The results are generally consistent and can be explained by the measurement characteristics and differences between the involved data sources.

As a general conclusion, it can be stated that the validation of the EU-DEM dataset yields overall values within specifications.

Furthermore, the detailed validation provides valuable insights into the characteristics of the EU-DEM elevation data, which will improve its utilization potential and help to prepare for the planned update of EU-DEM.

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1 Introduction

Digital Elevation Models (DEMs) provide fundamental information that is required across a broad set of application areas, each with different technical and usage requirements. The EU-DEM has been developed in response to an urgent need for continent-wide elevation data at 1 arc-second (approximately 30m x 30 m) posting, and at an overall vertical resolution of approximately 5m (European Commission 2009).

As no single data source provides consistent and complete pan-European coverage the EU-DEM has arrived from DEM fusion techniques combining data from different sources into a single, consistent and homogeneous elevation dataset. The fusion process relied mainly on data from ASTER GDEM and SRTM but also, in latitudes over 60º N, using elevation data from freely available Russian topomap series. The EU-DEM is further edited to ensure that water features are adequately represented and in order to arrive at a mid-scale digital elevation model, for instance to be used for modelling purposes on a river catchment basis.

Validation of the vertical accuracy of the EU-DEM is of critical importance to ensure that the elevation data achieve the accuracy of the specifications. The primary challenge in validating a pan-European elevation model is obtaining a useful reference data set that is accurate enough and has suitable coverage to encompass the entire area of interest. NASA's Ice, Cloud and land Elevation Satellite (ICESat) employing the Geoscience Laser Altimeter System (GLAS) has collected a unique set of full-waveform Light Detection And Ranging (LiDAR) data with global coverage during campaigns that began in 2003 and ended late 2009.

This ICESat/GLAS system provides a consistently referenced elevation data set with unprecedented accuracy and quantified measurement errors that can be used to generate Ground Control Points (GCPs) with a vertical accuracy high enough for validating the EU-DEM.

The objective of this specific document is to present the methods and implementation of statistical procedures for the validation of the EU-DEM vertical accuracy based on ICESat data. The validation results is needed to document the current vertical accuracy relative to the specification standards and to clarify potential issues with EU-DEM that need to be targeted for the planned upgrade of EU-DEM.

2 Data and Methodology

2.1 EU-DEM

The EU-DEM provides Pan-European elevation data at 1 arc-second (+/-30 meters) postings. The EU-DEM provides full coverage of the EEA countries (i.e. the so called EEA39) consisting of 33 member states and 6 cooperating ones. Area wise the EU-DEM covers 5.84M km². The EU-DEM is a hybrid product based mainly on SRTM and ASTER GDEM but also public available Russian topographic maps for regions north of 60^{o}N latitude. The data are fused by a weighted averaging approach and it has been generated as a contiguous dataset divided into 1 degree by 1 degree tiles (cf. Figure 1). The spatial reference system is geographic, lat/lon with horizontal datum ETRS89, ellipsoid GRS80 and vertical datum EVRS2000 with geoid EGG08.

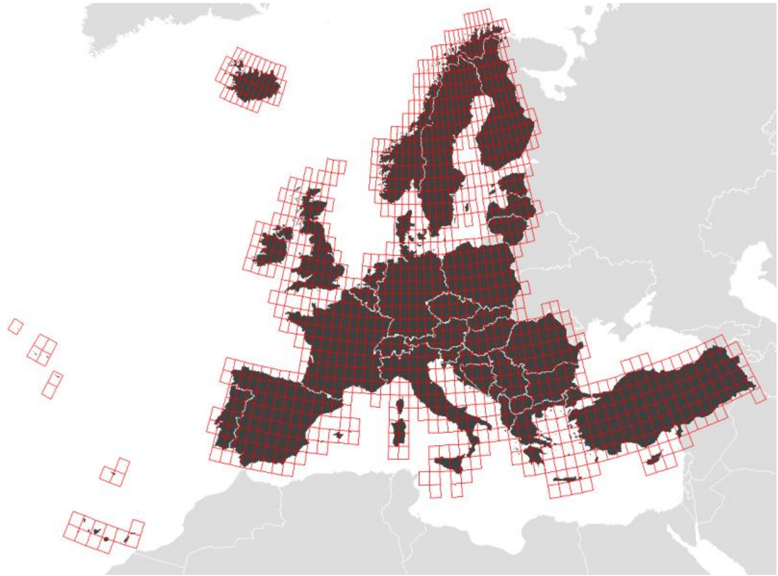

Figure 1. EU-DEM geographic coverage and tiling system.

The EU-DEM was requested to be produced according to a set of mandatory and optional requirements, and with a targeted overall vertical accuracy of 2 m RMSE, with options for vertical differentiated accuracies in different slope categories i.e. 1 m RMSE in lowlands (<10% slope); 2 m RMSE in midlands (10-30% slope) and 5 m RMSE in mountains (>30% slope). The target accuracy was however comprised in the final accepted offer for EU-DEM which was accepted with a vertical accuracy of +/- 7 meters RMSE with no differentiation of the vertical accuracy. Please refer to Appendix 1 for the original EU-DEM requirements and the final accepted specifications in response to the tender process.

2.2 ICESat Global Land Surface Altimetry Data

The main objective of the Geoscience Laser Altimeter System (GLAS) instrument on-board the NASA ICESat satellite was to measure ice sheet elevations and changes in elevation through time. Secondary objectives included measurement of cloud and aerosol height profiles, land elevation and vegetation cover, and sea ice thickness.

GLAS includes a laser system to measure distance, a Global Positioning System (GPS) receiver, and a star-tracker attitude determination system. The laser transmits short pulses (4 nano seconds) of infrared light (1064 nanometers wavelength) and visible green light (532 nanometers). Photons reflected back to the spacecraft from the surface of the Earth and from the atmosphere, including the inside of clouds, are collected in a 1 meter diameter telescope. Laser pulses at 40 times per second will illuminate spots (footprints) 70 meters in diameter, spaced at 170-meter intervals along Earth's surface (Schutz et al. 2005).

The distance from the spacecraft to clouds and to Earth's surface is determined from measurements of the time taken for the laser pulses to travel to the reflecting objects and return. The height of the spacecraft above the center of Earth are determined from information collected by the GPS receiver in GLAS and a GPS network operated around the world for other purposes. The pointing of the laser beam, relative to Earth's center is determined by the star-tracker system. The knowledge of the laser pointing and the spacecraft position are combined to calculate the precise location of the footprint on the surface to a few meters' accuracy (Zwally et al. 2002; Schutz et al. 2005).

The elevation of the surface at each laser footprint is the height of the spacecraft minus the measured distance to the surface. A standard parameterization is used to calculate surface elevation for ice sheets, oceans, and sea ice, using the elevation of the maximum peak and no more than two Gaussian functions with a minimum spacing of 30 ns (4.5 m) between Gaussian centers. For land elevations, the centroid of the return signal is used; a maximum of six Gaussians is allowed with 5 ns (75 cm) minimum spacing. For land surfaces, the algorithm characterizes the return pulse by fitting Gaussian distributions to each mode (peak) in the waveform. Surface elevation over land is derived from the centroid of the return.

Over most of the ice sheets, the accuracy of each elevation measurement is at sub-decimeter level. Over land, however, the vertical accuracy of the elevation measurements is less due to the effect of surface roughness i.e. the combined effect of slope, vegetation and cultural features. Still, according to Carabajal (2011) rigorous analysis has shown that for low relief locations in open terrain the ICESat data return elevation values with sub-meter accuracy.

Data was collected from February, 2003 to October, 2009 during approximately month long observation periods, three times per year through 2006 and twice per year thereafter. These altimetry profiles provide a highly accurate and consistently referenced elevation data set with quantified errors. Three lasers were used sequentially during the mission. Still, only data acquired by Laser 3 was used for EU-DEM validation, since the spatial distribution of the footprint energy was Gaussian with a diameter of about 50 meters, and hence more suitable to evaluate a 30 m resolution elevation model. Laser 3 coverage period is from October 2004 to October 2009.

There are several standard ICESat data products (cf. http://nsidc.org/data/icesat/data.html). For the EU-DEM validation GLAH14 (GLAS/ICEsat L2 Global Land Surface Altimetry Data) product was obtained. Strict editing criteria were applied to the ICESat data in order to select ICESat records with the highest possible accuracy and to exclude ICESat data with potential error sources that could degrade its accuracy. First, filtering of invalid or critical values was performed using the internal quality flags in the ICESat GLAH14 data files (cf. Table 1).

Table 1. ICESAT GLAH14 data quality flags.

Attribute	Group	Description	Flag values and meanings
elev_use_flg	Data_40HZ/Quality	Flag indicating whether the elevations on this record should be used.	0 (valid) 1 (not_valid)
sat_corr_flg	Data_40HZ/Quality	Saturation Correction Flag; Indicates if the returns is saturated or not.	0 (not_saturated) 1 (inconsequential 2 (applicable) 3 (not computed) 4 (not applicable)
d_satElevCorr	Data_40HZ/Elevation_Corrections	Correction to elevation for saturated waveforms. This correction has NOT been applied to the data.	If this is zero then no correction is necessary and the signal is assumed not saturated
rng_uqf_xxxx	Data_40HZ/Quality	Range offset quality flags	0 (valid) 1 (not_valid)
elv_cloud_flg	Data_40HZ/Elevation_Flags	Cloud contamination; Indicates probable cloud contamination	0 (false) 1 (true)

From Table it is seen that a non-zero data use or frame quality flag indicates a less than ideal situation during processing and the record was therefore excluded for further interpretation. In addition extreme outliers can be attributed to cloud contamination why ICESat locations with elevations deviating more than 50 meters from the EU-DEM were excluded using an ICESat and EU-DEM difference edit. Finally, laser beams with off-nadir pointing (> 1^o) were also exclude from the analysis as the off-nadir pointing introduces errors that are a function of the angle with which the surface is intercepted.

2.3 Ancillary data

A number of ancillary data sources were used to support the selection of ICESat data records for the assessment of the fundamental vertical accuracy as well as supplemental and consolidated accuracies. These data sets included the high resolution and pan-European maps of soil sealing and forest cover for the reference year 2006; the 2006 Corine land cover; the EU-DEM derived slope map (Table 2) as well as national borders for the EEA39 countries.

Table 2. List of ancillary layers used for the EU-DEM statistical validation.

Theme	Description	Resolution	Reference Year	Source
Slope	Slope derived from EU-DEM	25 meters	2000	JRC, 2012
Forest cover	Pan-European Forest/Non-Forest Map (version 1.0)	25 meters	2006	JRC, 2010
Soil sealing	Raster data set of built-up and non-built-up areas including continuous degree of soil sealing ranging from 0 - 100% (revised version)	20 meters	2006	EEA, 2013
Land cover	Raster data on land cover for the CLC2006 inventory (version 17/2013)	100 meters	2006	EEA, 2013

2.4 Data comparison

ICESat GLA14 data contain land elevations with respect to the TOPEX/Poseidon-Jason ellipsoid which is about 70 cm smaller than the WGS 84 ellipsoid. As a consequence, comparison of ICESat elevations to those obtained from other sources must take into account the potential effect of ellipsoid differences. The comparison of EU-DEM with ICESat elevations was done using WGS84 as the reference ellipsoid. First, the ICESat footprint locations were converted to the WGS84 ellipsoid using the empirically derived formula provided by NSIDC[1] . Hereafter, the EU-DEM orthometric heights were transformed back to ellipsoidal heights by applying the European Gravimetric Quasigeoid model EGG2008[2] and assuming the GRS80 and WGS84 ellipsoids being equal[3].

For every ICESat footprint the corresponding EU-DEM elevation and slope values was computed as the mean and standard deviation within a 3x3 pixel neighbourhood. Moreover, values for each of the ancillary data layers were also extracted for each ICESat footprint including i.e. forest cover and soil sealing percentage as derived within a 3x3 neighbourhood as well as the direct extraction of the CORINE land cover classes and country labels.

The EU-DEM fundamental accuracy was evaluated using ICESat footprints located in open low relief terrain only, while the supplemental and consolidated accuracies were derived using different selection procedures based on the combined usage of forest cover and soil

[1] The National Snow and Ice Data Center (NSIDC) - http://nsidc.org/data/icesat/

[2] Dr.-Ing. Heiner Denker (personal communication 2014).

[3] This is justified by the fact that the WGS 84 originally used the GRS 80 reference ellipsoid, but has undergone some minor refinements in later editions since its initial publication. Most of these refinements are important for high-precision orbital calculations for satellites but have little practical effect on typical topographical uses.

sealing percentages, slope categories as well CORINE land cover. Accuracy measures are given not only for EU-DEM as whole but also (when applicable) per country in order to reveal any potential regional biases.

2.5 Statistical validation

The procedure for statistical validation of the EU-DEM vertical accuracies is based on industry standards as put forward in the “Guidelines for Digital Elevation Data” published by the National Digital Elevation Program (NDEP 2004).

2.5.1 Reference data

Accuracy assessment of the DEM is carried out by means of independent reference data. In this case independent means having no connection with the production of the EU-DEM. Further, requirements of the reference data relates to validity and representativeness.

As for the validity of reference data then it is normal to presume that reference data are error free and that discrepancies therefore can be attributable to the tested product which is assumed to have lower accuracy. However, reference data are not always error free and the general rule of thumb, to ensure trustworthy validation, is to use reference data with accuracies at least three times greater than the expected accuracy of the product being tested. It is generally recognised that ICESat data after quality filtering achieve sub-meter accuracies over low relief locations (Carabajal 2011) and ICESat data therefore makes an adequate reference for EU-DEM which has been requested to meet an overall vertical accuracy in the order of +/- 5 meters.

Representativeness refers to the number and distribution of reference data i.e. the number of reference data should be high enough to fulfil statistical requirements but also distributed to reflect the geographical area of interest. The main advantage of using ICESat for the validation of EU-DEM is the fact it represent a single homogenous reference dataset with continent wide representation (cf. Figure 2).

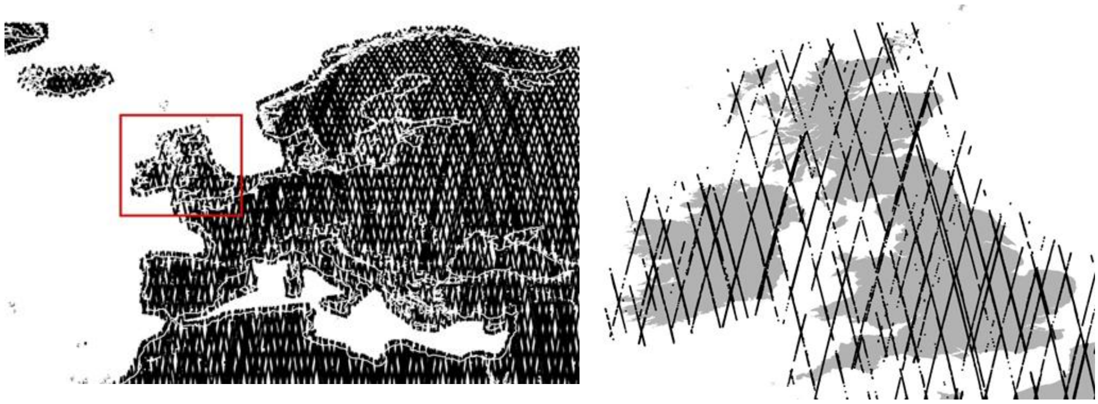

Figure 2. Overview map over ICESat paths and footprints over Western Europe (left) and zoom window over the British Islands (right).

The exact number of reference points available for the validation varies with the ICESat selection criteria which are being dictated by the requirement for the different accuracy calculations (cf. fundamental vs. supplemental and consolidated accuracy measures). The critical sample size, however, can be estimated to be 384 samples using the multi-nominal distribution with a confidence level of 95% and a margin of error of 5% (Congalton and Green 2009). Any accuracy measure based on samples below the critical sample size will therefore be omitted or clearly marked with an asterisk to indicate the result should be treated cautiously.

2.5.2 Measures of Accuracy

Error! Reference source not found. summarises the accuracy measures and associated tatistics that will be used for the reporting of EU-DEM vertical accuracy.

Table 3. Accuracy measures for EU-DEM validation.

Number of checkpoints	$\boldsymbol{n}$
Vertical error	$\Delta h = h_{EU-DEM} - h_{ICESat}$
Root mean square error	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \Delta h_i^2}$
Mean error (or bias)	$\hat{u} = \frac{1}{n}\sum_{i=1}^{n} \Delta h_i$
Standard deviation	$\hat{\sigma} = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n} (\Delta h_i - \hat{u})^2}$
Linear error at 95% confidence level	LE95
95th percentile	P95
Threshold for outliers	$\lvert \Delta h \rvert \geq 3 \cdot RMSE$

The measures are based on the assumption of normal error distribution with no outliers. Still, outliers and non-normal distributed data occur especially over topographic complex and/or non-open terrain. The approach to deal with outliers is to remove them by applying a threshold. For example, the threshold can be selected from an initial calculation of the accuracy measures. The threshold for eliminating outliers in the EU-DEM validation is selected as three times the Root Mean Square Error (RMSE), i.e. an error will be classified as an outlier if $\Delta h_i > 3 \cdot \mathrm{RMSE}$. In cases where outlier removal is not sufficient to achieve normal distributed errors a nonparametric testing method (the 95th Percentile) can be used.

2.5.3 Processing workflow

The use of ICESat data requires working with millions of potential reference points across the European continent and the EU-DEM statistical validation has therefore followed a processing workflow based on automated tasks to the largest extent possible (cf. Figure 3).

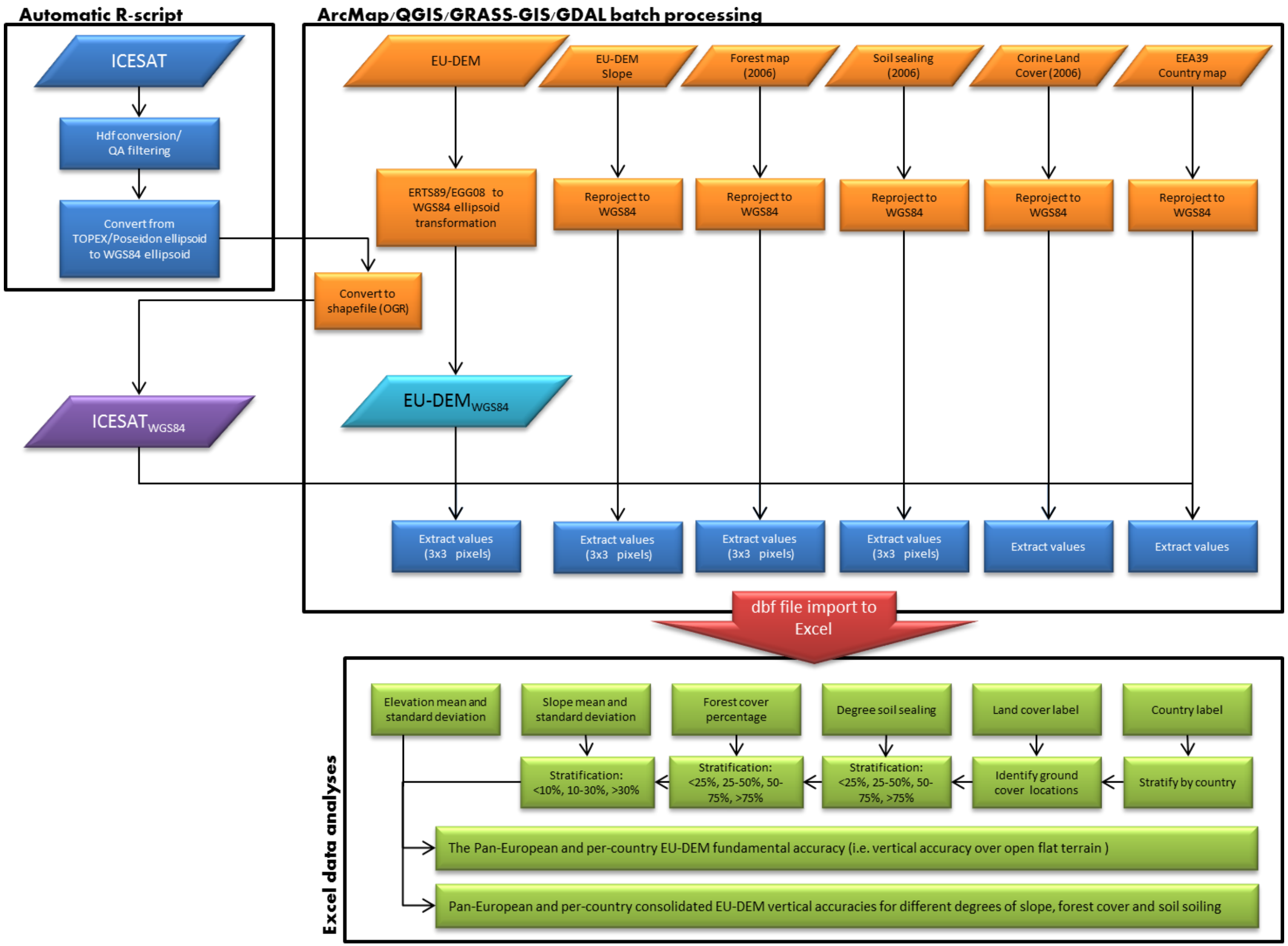

Figure 3. Processing workflow for the EU-DEM statistical validation.

3 Results

3.1 Fundamental accuracy

After quality filtering and exclusion of water and wetlands (CORINE land cover $\leq$ 35) a selection procedure was used to extract ICESat locations characterised with short or non-vegetated areas (Forest cover percentage = 0) and with low relief (< 10^{o} slope). The selection process returned closed to appr. 1 mio. ICESat records suitable for assessing the fundamental accuracy of EU-DEM. The difference between EU-DEM and the selected ICESat elevations returns a distribution of errors that follows a normal distribution with no obvious bias i.e. being centred close to zero (Figure 4).

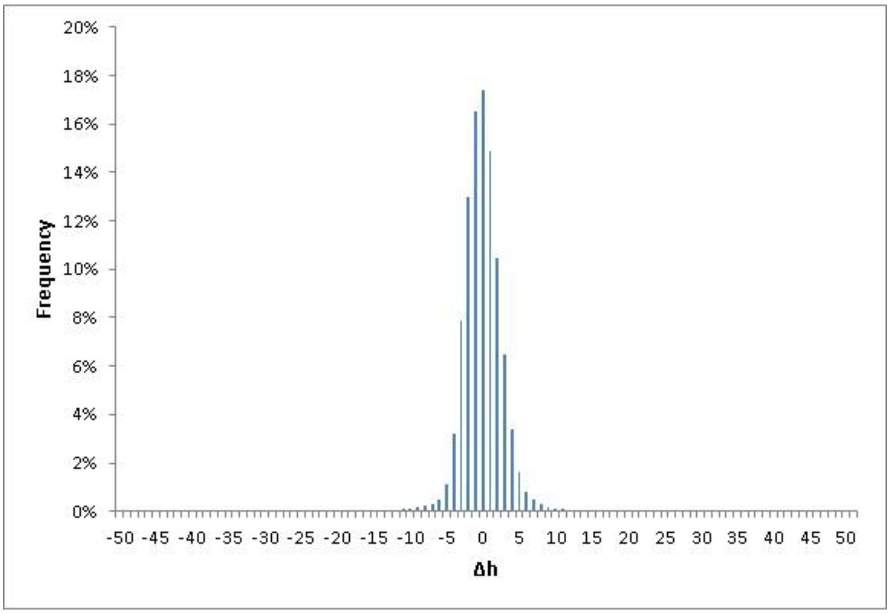

Figure 4. Histograms of errors (Δh) for fundamental accuracy assessment of EU-DEM.

The summary statistics for the assessment of the fundamental accuracy is seen in Table 4. Excluding Andorra, Lichtenstein and Luxembourg as well as some Island regions (i.e. Canaries, Isle of Man, Jersey and Malta) then the ICESat data records are sufficient to provide reliable estimate of within country EU-DEM fundamental accuracy. For all EEA countries except Iceland (9.41 m), Norway (5.75 m) and Sweden (7.41 m) the RMSE accuracies are less than 4 meters. Overall the RMSE error for EU-DEM as a whole is 2.90 meters which translate into a Linear Error of 5.69 meters at the 95 percent confidence level.

Table 4. Results of the EU-DEM fundamental accuracy for entire EEA39.

	n	Mean error (m)	St.dev. (m)	RMSE (m)	LE95 (m)
Albania	1937	-1,76	1,68	2,44	4,77
Andorra	1*	7,41	n.a.	7,41	14,53
Austria	4757	-1,84	1,84	2,60	5,09
Belgium	6567	-0,45	1,51	1,58	3,09
Bosnia and Herzegovina	2665	-1,88	1,90	2,68	5,25
Bulgaria	16263	-0,20	1,78	1,79	3,51
Canary Islands	56*	1,57	2,41	2,86	5,60
Croatia	9953	-1,61	2,07	2,62	5,13
Cyprus	3980	0,27	1,51	1,54	3,01
Czech Republic	8803	-1,04	2,07	2,31	4,53
Denmark	19153	-0,75	1,54	1,71	3,36
Estonia	7170	2,53	2,38	3,47	6,80
Finland	43070	-0,45	3,43	3,46	6,78
France	108029	-0,49	1,85	1,91	3,74
Germany	74807	-1,28	1,66	2,10	4,12
Greece	14723	-0,43	1,95	2,00	3,92
Hungary	36385	-2,38	1,42	2,77	5,43
Iceland	7584	-6,73	6,58	9,41	18,45
Ireland	18204	-0,19	1,74	1,75	3,44
Isle of Man	50*	2,17	2,27	3,13	6,13
Italy	48422	-0,88	2,01	2,20	4,31
Jersey	10*	-0,38	1,98	1,91	3,75
Latvia	11792	-1,20	2,39	2,67	5,23
Liechtenstein	18*	0,23	1,52	1,49	2,92
Lithuania	20697	-2,96	1,47	3,31	6,48
Luxembourg	268*	-1,01	1,86	2,11	4,14
Malta	2*	2,20	1,86	2,56	5,02
Moldova	3589	-1,38	1,79	2,26	4,42
Montenegro	768	-1,35	1,77	2,23	4,36
Netherlands	13686	-0,85	1,40	1,63	3,20
Norway	18560	0,03	5,75	5,75	11,28
Poland	93946	-2,38	1,60	2,87	5,62
Portugal	12005	0,58	2,03	2,12	4,15
Romania	54010	-1,60	1,64	2,29	4,50
Serbia	15515	-2,65	1,76	3,18	6,24
Slovakia	8973	-1,98	1,46	2,46	4,83
Slovenia	1229	-0,40	1,64	1,69	3,31
Spain	101529	0,33	1,86	1,89	3,70
Sweden	31850	0,83	7,36	7,41	14,52
Switzerland	1397	-1,44	2,22	2,65	5,19
Macedonia	1380	-0,75	1,74	1,89	3,71
Turkey	123275	1,70	1,91	2,56	5,01
United Kingdom	44101	0,72	1,90	2,03	3,98
Total	**991179**	**-0,56**	**2,85**	**2,90**	**5,69**

A plausible reason for the lower accuracy in north is the lack of SRTM data north of 60^{o}N and hence the reliance of ASTER GDEM data alone or the combination of ASTER GDEM and Russian topographic maps. Accordingly, the EU-DEM fundamental accuracy was further investigated for latitudes north and south of 60°N respectively.

3.1.1 Latitudes south of 60°N

The approximately 900.000 ICESat records available for the region south of 60°N follow a normal distribution centred close to zero (cf. Figure 5).

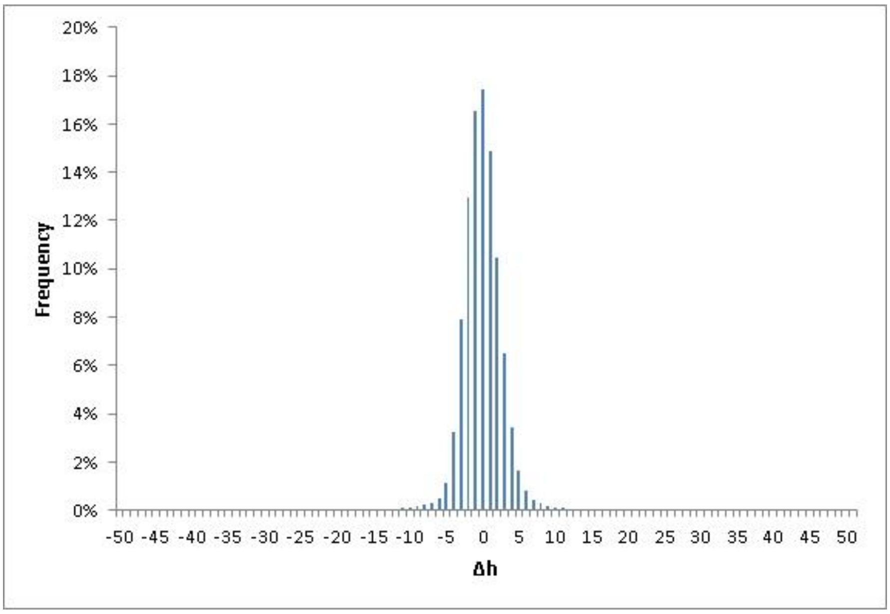

Figure 5. Histograms of errors (Δh) for fundamental accuracy at locations south of 60°N.

The summary statistics for the assessment of the fundamental accuracy for latitudes south of 60°N is seen in in Table 5. Excluding Andorra, Lichtenstein and Luxembourg, Finland as well as some Island regions (i.e. Canaries, Isle of Man, Jersey and Malta) then the ICESat data records are sufficient to provide reliable estimate of within country EU-DEM fundamental accuracy for the region south of 60°N. RMSE accuracies vary from a low of 1.39 meters in Cyprus to a maximum of 3.25 in Lithuania. Overall the RMSE error for EU-DEM south of 60°N is 2.23 meters which translate into a Linear Error of 4.37 meters at the 95 percent confidence level.

Table 5. Results of the EU-DEM fundamental accuracy for locations south of 60°N.

	n	Mean error (m)	St.dev. (m)	RMSE (m)	LE95 (m)
Albania	1926	-1,72	1,58	2,34	4,58
Austria	4704	-1,79	1,68	2,45	4,81
Belgium	6553	-0,45	1,46	1,52	2,99
Bosnia and Herzegovina	2635	-1,80	1,73	2,49	4,89
Bulgaria	16212	-0,19	1,71	1,72	3,37
Canary Islands	55*	1,77	1,92	2,60	5,09
Croatia	9842	-1,62	1,74	2,38	4,67
Cyprus	3960	0,28	1,36	1,39	2,72
Czech Republic	8734	-0,98	1,73	1,99	3,90
Denmark	19109	-0,74	1,48	1,66	3,25
Estonia	6848	2,18	1,65	2,73	5,35
Finland	23*	3,33	2,72	4,27	8,36
France	107550	-0,49	1,75	1,82	3,56
Germany	74524	-1,27	1,54	2,00	3,91
Greece	14631	-0,39	1,80	1,85	3,62
Hungary	36273	-2,37	1,35	2,72	5,33
Ireland	18137	-0,20	1,64	1,65	3,23
Isle of Man	50*	2,17	2,27	3,13	6,13
Italy	48153	-0,86	1,90	2,09	4,09
Jersey	10*	-0,38	1,98	1,91	3,75
Latvia	11615	-1,33	2,02	2,42	4,74
Liechtenstein	18*	0,23	1,52	1,49	2,92
Lithuania	20577	-2,96	1,34	3,25	6,36
Luxembourg	267*	-0,98	1,79	2,03	3,99
Malta	2*	2,20	1,86	2,56	5,02
Moldova	3571	-1,35	1,66	2,14	4,20
Montenegro	757	-1,24	1,52	1,96	3,85
Netherlands	13649	-0,83	1,32	1,56	3,05
Norway	1719	0,82	2,50	2,63	5,16
Poland	93576	-2,38	1,51	2,82	5,52
Portugal	11891	0,52	1,83	1,90	3,73
Romania	53737	-1,58	1,54	2,20	4,32
Serbia	15476	-2,64	1,70	3,14	6,16
Slovakia	8926	-1,96	1,36	2,38	4,67
Slovenia	1220	-0,39	1,47	1,52	2,97
Spain	101007	0,33	1,74	1,77	3,47
Sweden	13463	1,09	2,54	2,76	5,41
Switzerland	1376	-1,39	2,00	2,43	4,76
Macedonia	1368	-0,69	1,58	1,73	3,39
Turkey	122332	1,67	1,78	2,44	4,79
United Kingdom	43771	0,71	1,75	1,89	3,70
Total	**900247**	**-0,56**	**2,16**	**2,23**	**4,37**

3.1.2 Latitudes north of 60^{o}N

The approximately 83.500 ICESat records available for the region north of 60^{o}N follow a normal distribution with a slight negative bias of -0.8 meters (cf. Figure 6).

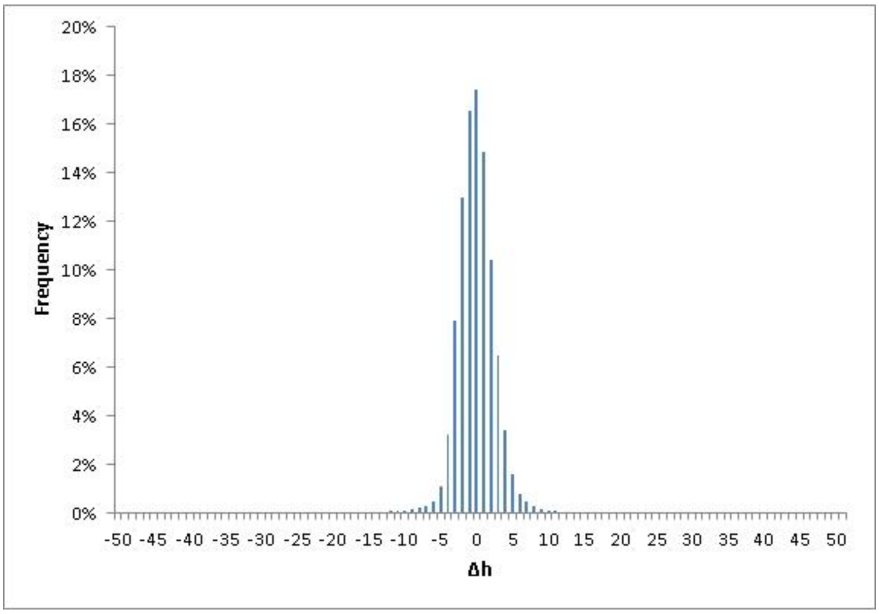

Figure 6. Histograms of the errors (Δh) for fundamnetal accuracy at locations north of 60^o N.

The summary statistics for the assessment of the fundamental accuracy for latitudes north of 60^{o}N is seen in Table 6. Excluding United Kingdom north of 60^{o}N then the ICESat data records are sufficient to provide reliable estimate of within country EU-DEM fundamental accuracy for the region north of 60^{o}N. RMSE accuracies vary from a low of 3.38 meters in Finland to a maximum of 8.63 meters in Iceland. Part of the explanation for the higher RMSE error for Iceland may be attributed to the high mean error of -6.27 meters. Overall the RMSE error for EU-DEM north of 60^{o}N is 5.19 meters which translate into a Linear Error of 10.18 meters at the 95 percent confidence level.

Table 6. Results of the EU-DEM fundamental accuracy for locations north of 60^{o}N.

	n	Mean error (m)	St.dev. (m)	RMSE (m)	LE95 (m)
Finland	42987	-0,44	3,35	3,38	6,63
Iceland	7361	-6,27	5,94	8,63	16,92
Norway	16583	-0,08	5,10	5,10	10,00
Sweden	16461	-0,02	6,88	6,88	13,48
United Kingdom	67*	-3,21	5,53	6,36	12,46
Grand Total	83459	-0,80	5,13	5,19	10,18

3.2 Supplemental and Consolidated Vertical Accuracies

The supplemental and consolidated accuracy assessments are performed to investigate the effect of terrain and ground cover on the EU-DEM elevation biases. The deviation of the northern Scandinavian countries in terms of EU-DEM fundamental accuracy will also transpose into the analysis of supplemental and consolidated accuracies why the assessment of EU-DEM elevation bias due to slope and forest cover is made separately for the regions north and south of 60^{o}N. The same separation was not deemed necessary for the investigation of bias due to urban land cover as the ICESat footprint locations with dense urban land cover is insignificant in the region north of 60^{o}N.

3.2.1 Slope

The results of the investigation of slope on EU-DEM elevation biases are presented below for the regions south and north of 60^{o}N respectively.

3.2.1.1 Latitudes south of 60^{o}N

After quality filtering and exclusion of water and wetlands (CORINE land cover < 35) a selection procedure was used to extract non-urban (soil sealing=0) ICESat locations with short or no vegetation (Forest cover percentage = 0). The selection process returned around 875.000. ICESat records with the majority located in lowlands (<10%) and only 4.1% located in moderate terrain and a mere 0.2% located in mountainous terrain (>30%).The error distribution from the EU-DEM and ICESat elevation difference follows a normal distribution centred on zero for all three slope categories, but the distributions widen as the slope categories increases (Figure 7).

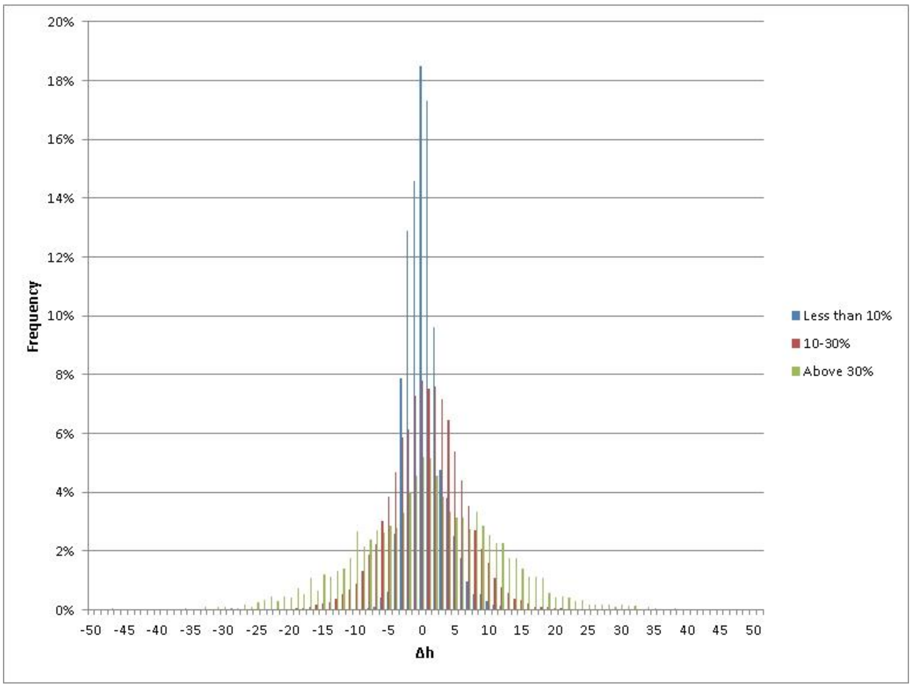

Figure 7. Histograms of the errors (Δh) for the assessment of elevation bias due to slope at locations south of 60^{o}N.

The summary statistics for the vertical accuracy assessment of slope categories is seen in Table 6, and showing a clear trend towards higher variability and higher errors for the steeper slope categories.

Table 7. Results of the EU-DEM elevation bias due to slope for locations south of 60^{o}N.

Slope category*	n	Mean error (m)	Std (m)	RMSE (m)	LE95 (m)	Optional RMSE specifications (m)**
Less than 10%	839953	-0,52	2,23	2,29	4,49	1
10-30%	36220	0,19	3,98	3,98	7,80	2,5
Above 30%	1785	0,16	4,35	4,35	8,53	5
Total	877958	-0,49	2,34	2,39	4,69	7

** Mean slope within 3x3 pixel neighbourhood (i.e. 75x75 m) at the latitude and longitude location of each ICESat footprint*

*** The tender specifications operated with options for a vertical differentiated accuracy of EU-DEM according to slope categories.*

3.2.1.2 Latitudes north of 60°N

The filtering and selection process returned around 95.000. ICESat records for the region north of 60°N with the majority (87.9%) located in lowlands with less than <10 slope and only 8.2% located in moderate terrain (10-30%) and a mere 0.8% located in mountainous terrain (>30%). For the region north of 60°N and for locations with less than 30% slope the errors follow a normal distribution centred on zero. The error distribution for locations with more than 30% slope is also centred on zero but the distribution is wider with significant more errors above +/- 10 meters (Figure 8).

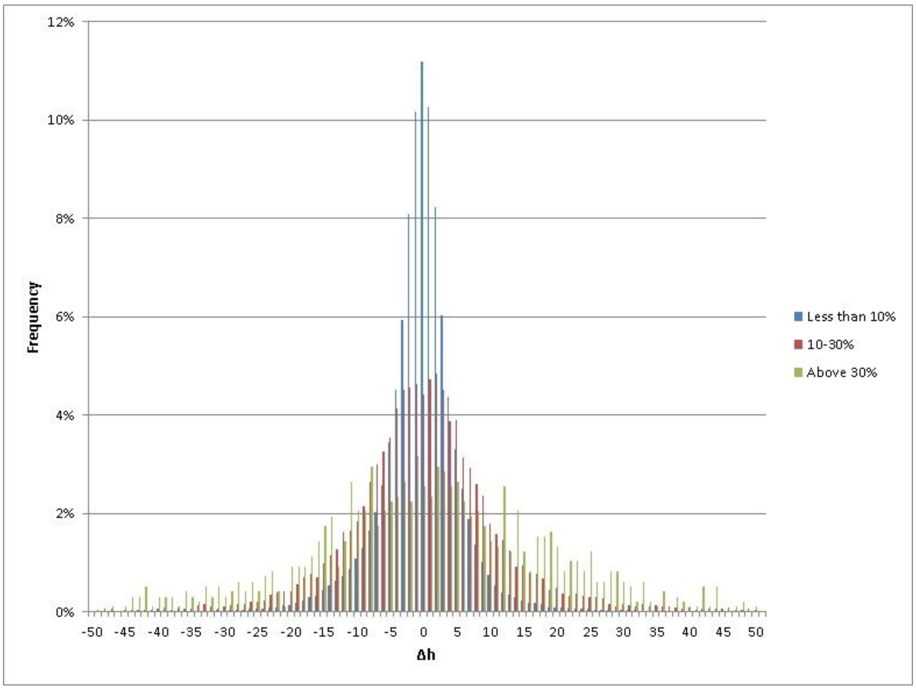

Figure 8. Histograms of the errors (Δh) for the assessment of elevation bias due to slope at locations north of 60° N.

The summary statistics for the vertical accuracy assessment of slope categories is seen in Table 8, and showing a clear trend towards higher variability and higher errors for the steeper slope categories.

Table 8. Results of the EU-DEM elevation bias due to slope for locations north of 60°N

Slope category*	n	Mean error (m)	Std (m)	RMSE (m)	LE95 (m)	Optional RMSE specifications (m)**
Less than 10%	83411	-0,86	5,46	5,53	10,83	1
10-30%	10651	-0,51	8,43	8,45	16,56	2,5
Above 30%	781	0,14	10,80	10,80	21,16	5
Total	94843	-0,81	5,93	5,99	11,73	7

** Mean slope within 3x3 pixel neighbourhood (i.e. 75x75 m) at the latitude and longitude location of each ICESat footprint*

*** The tender specifications operated with options for a vertical differentiated accuracy of EU-DEM according to slope categories.*

3.2.2 Forest cover

The results of the investigation of forest cover on EU-DEM elevation biases are presented below for the regions south and north of 60°N respectively.

3.2.2.1 Latitudes south of 60°N

After quality filtering and exclusion of water and wetlands (CORINE land cover < 35) a selection procedure was used to extract low relief (< 10° slope) ICESat locations with a forest cover percentage higher than 0%. The selection process returned around 93.000 ICESat records and the difference between EU-DEM and the selected ICESat elevations returned a distribution of errors following a normal distribution with a mean around +2 meters (Figure 9).

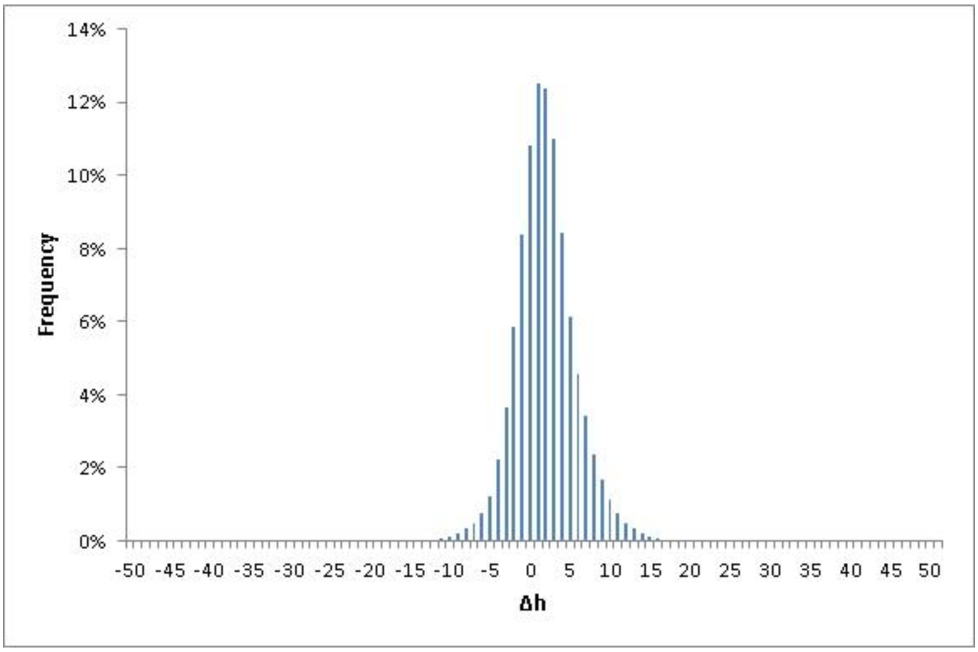

Figure 9. Histograms of the errors (Δh) for the assessment of elevation bias due to forest cover south of 60°N.

The summary statistics for the vertical accuracy assessment of different forest cover categories for locations south of 60oN is seen in Table 9, and showing a clear trend towards higher variability and higher mean errors for higher degrees of forest cover, which is also being illustrated in Figure 10.

Table 9. Results of the EU-DEM elevation bias due to forest cover for locations south of 60°N.

Forest cover*	n	Mean error (m)	Std.dev. (m)	RMSE (m)	LE95 (m)
0-25%	8737	1,66	3,86	4,20	8,24
25-50%	8638	1,74	3,98	4,35	8,52
50-75%	9722	1,59	4,19	4,48	8,78
75-100%	66109	1,93	4,17	4,60	9,01
Total	93206	1,85	4,13	4,53	8,87

** Degree forest cover within 3x3 pixel neighbourhood (i.e. 75x75 m) at the latitude and longitude location of each ICESat footprint.*

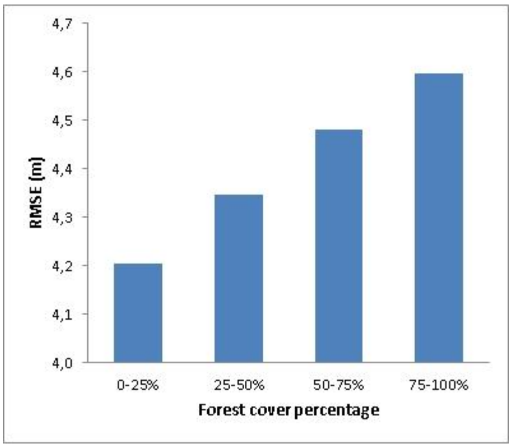

Figure 10. Variability of RMSE relative to forest cover percentages for locations south of 60°N.

3.2.2.2 Latitudes north of 60°N

After quality filtering and exclusion of water and wetlands (CORINE land cover < 35) a selection procedure was used to extract low relief (< 10° slope) ICESat locations with a forest cover percentage higher than 0%. The selection process returned around 125.000 ICESat records and the difference between EU-DEM and the selected ICESat elevations returned a distribution of errors following a normal distribution with a mean around -1.5 meters (Figure 11).

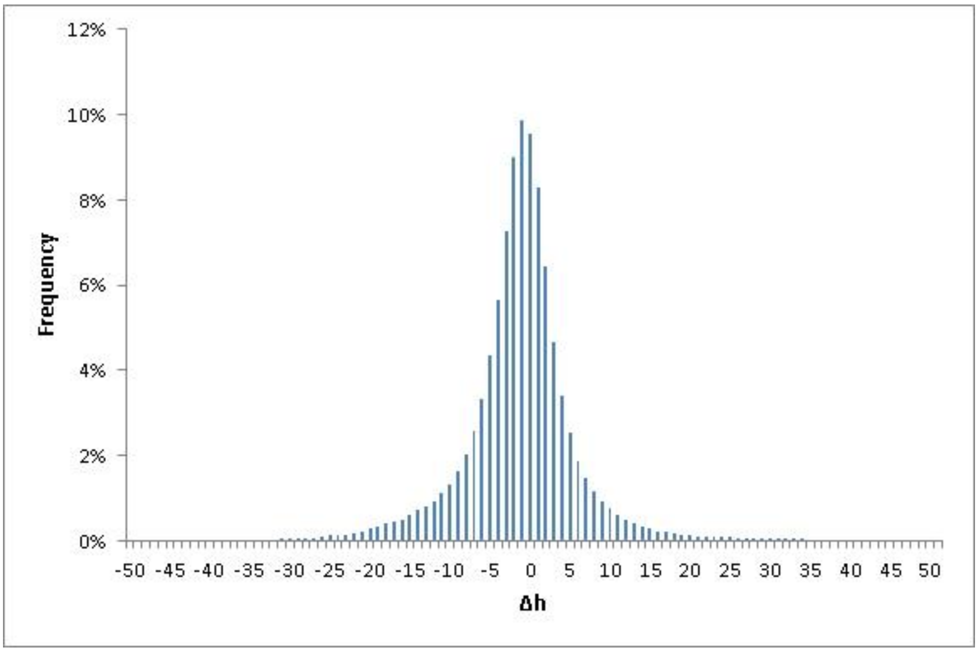

Figure 11. Histograms of the errors (Δh) for the assessment of elevation bias due to forest cover at locations north of 60°N.

The summary statistics for the vertical accuracy assessment of different forest cover categories for locations north of 60°N is seen in

Table 10 and showing a clear trend towards higher variability and higher mean errors for the steeper slope categories, which is being further illustrated in Figure 12.

Table 10. Results of the EU-DEM elevation bias due to forest cover for locations north of 60°N.

Forest cover*	n	Mean error (m)	Std.dev. (m)	RMSE (m)	LE95 (m)
0-25%	12299	-0,73	5,43	5,48	10,74

25-50%	13618	-0,94	5,45	5,53	10,84
50-75%	14759	-1,24	5,45	5,59	10,95
75-100%	82680	-1,93	5,40	5,74	11,25
Total	123356	-1,62	5,44	5,67	11,12

** Degree forest cover within 3x3 pixel neighbourhood (i.e. 75x75 m) at the latitude and longitude location of each ICESat footprint*

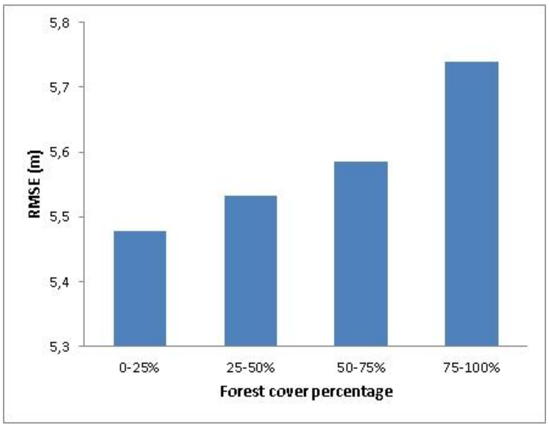

Figure 12. Variability of RMSE relative to forest cover percentages for locations north of 60°N.

3.2.3 Urban land cover

This section summarizes the outcome of the investigation of urban land cover on EU-DEM elevation biases. No separation is made between location north and south of 60°N for the simple fact that the ICESat records with urban land cover over 60°N is very limited.

After quality filtering and exclusion of water and wetlands (CORINE land cover < 35) a selection procedure was used to extract ICESat location with urban land cover (CORINE Classes 1,2 and 3) and with soil sealing larger than 0%. The selection process returned around 46.000. ICESat records and the difference between EU-DEM and the selected ICESat elevations showed a distribution of errors following a normal distribution with a slight negative bias of -0.75 meters.

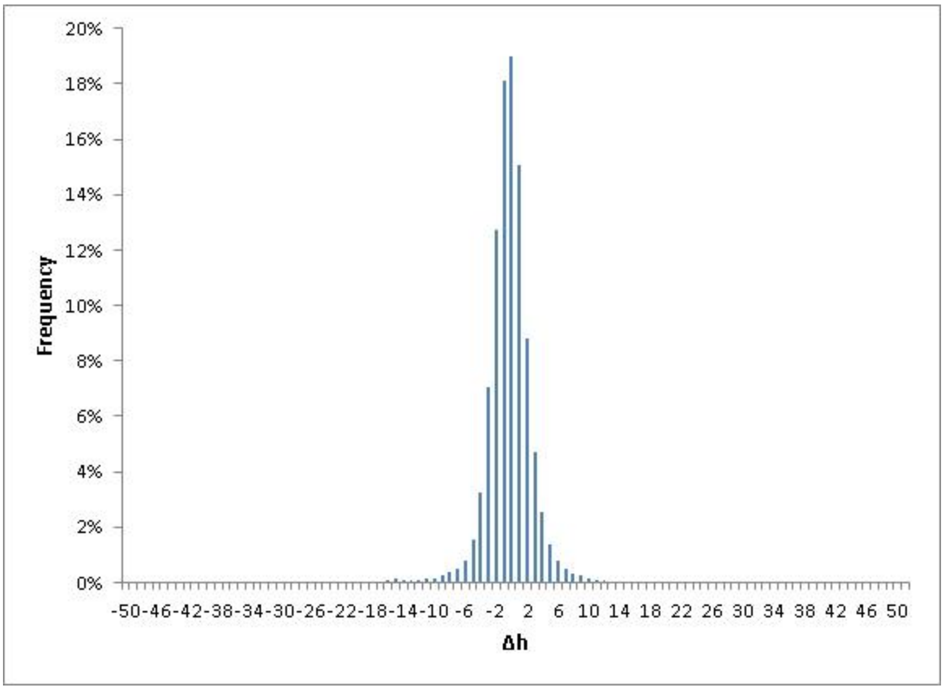

Figure 13. Histograms of the errors (Δh) for the assessment of EU-DEM elevation bias over urban areas.

The summary statistics for the vertical accuracy assessment of EU-DEM over urban areas with different degrees of soil sealing is seen in Table 11. The statistics show a consistent trend towards higher mean error for higher degrees of soil sealing, while the RMSE errors are more ambiguous with higher errors for the lowest and highest degrees of soil sealing.

Table 11. Results of the EU-DEM elevation bias due to urban land cover.

Soil sealing*	n	Mean error (m)	Std.dev. (m)	RMSE (m)	LE95 (m)
0-25%	20815	-0,58	2,53	2,59	5,08
25-50%	9912	-0,63	2,27	2,36	4,62
50-75%	9508	-0,85	2,16	2,32	4,54
75-100%	6097	-1,34	2,16	2,55	4,99
Grand Total	46332	-0,75	2,37	2,48	4,87

** Degree soil sealing within 3x3 pixel neighbourhood (i.e. 60x60 m) at the latitude and longitude location of each ICESat footprint*

4 Discussion

The ICESat data archive provides several millions records of well-distributed, highly accurate and consistent elevation data with quantified errors. For the validation of EU-DEM strict editing criteria was applied to generate a high quality Ground Control Points (GCPs) database from the ICESat records with sub-meter vertical accuracies and a horizontal accuracy around 5 meters.

Overall the EU-DEM vertical accuracy is assessed to have an RMSE of 2.90 meters with a slight mean error of -0.56 meters. This overall accuracy however, masks a distinct difference between latitudes south and north of 60^{o}N. The calculation of the vertical accuracy for these two regions separately revealed an overall vertical RMSE accuracy of 2.23 meters (mean error -0.56 m) for the region south of 60N and an RMSE error of 5.19 meters (mean error of -0.8 m) for the region north of 60N. The lower performance for the region north of 60N can be explained by the lack of SRTM data and hence the heavier reliance on ASTER GDEM and Russian topographic maps. This observation is underpinned by the difference in EU-DEM accuracies for the regions in Norway and Sweden which resides south and north of 60°N respectively. The RMSE error for locations south of 60N in Sweden is 2.76 m compared to 6.88 m for regions north of 60N. Similar in Norway the RMSE error for locations south of 60N is an estimated 2.63 m compared to 5.10 m for the region north of 60N.

When looking into the potential elevation biases caused by relief and ground cover categories it is observed that that EU-DEM becomes a less reliable measure of ground topography as the terrain slope becomes steeper and the density of the tree cover increases.

When comparing height differences between EU-DEM and ICESat versus slope categories the RMSE error increases with slope. This tendency has a dual explanation. On one hand it is recognised that the accuracy of the ICESat data is degraded with increasing incidence angle between the laser beam vector and the normal to the surface slope, causing waveform broadening. This error, however, was minimized by excluding data acquired when the laser beam was pointed off from nadir by more than 1°. Therefore, and on the other hand, the tendency is believed to be a true reflection of degrading EU-DEM accuracies in steeper terrain, and as corroborated by other studies (cf. Figure 14).

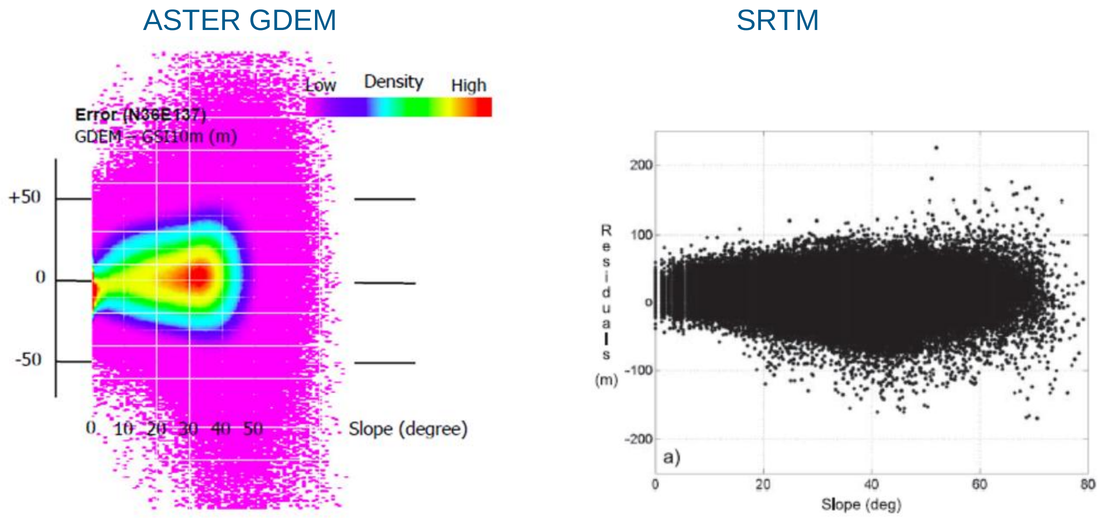

Figure 14. Graph of ASTER GDEM and SRTM vertical errors plotted against slope (sources: ASTER GDEM Validation Team 2009 and Falorni *et al.* 2005)

For both regions there is an increase in RMSE with increasing tree cover and a clear observable mean error of +1.85 meters south of 60N and -1.62 north of 60°N. In south the difference can be explained by the fact that ASTER GDEM is a first reflective surface model representing the highest reflective surface of ground features captured by the sensor, whereas the ICESat reference elevation is based on the centroid rather than the first return. Similar, and although the SRTM C-band radar penetrates slightly less than halfway into the canopy the phase center will shift upward with increased tree cover and thereby increasing the distance to the centroid height of ICESat (cf. Figure 15).

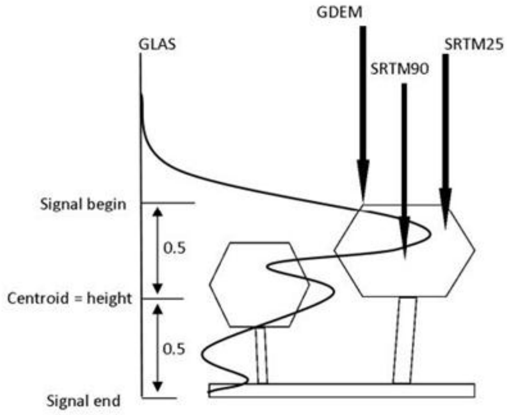

Figure 15. ICESat waveform over forest canopy relative to wavelengths signal from SRTM and ASTER GDEM (from Ensle et al 2012).

It is more difficult to explain the observed negative bias in the region north of 60N where ASTER GDEM is supposedly dominating, and hence a positive mean error would have been expected. The reason for the observed negative bias may however be explained by specific processing steps for EU-DEM. First of all significant areas of the ASTER GDEM was identified as voided due to cloud cover and for the region north of 60N these areas was filled using Russian topographic maps which presumably make reference to the bare earth.

Finally, the potential bias of EU-DEM was investigated over urban areas and revealing an overall RMSE accuracy of 2.45 meters and a slight negative mean error of -0.75. The low RMSE accuracy is expected since all data sources ASTER GDEM, SRTM and ICESat can be considered first reflective surfaces over sealed areas. The negative bias may be explained by the fact that the ICESat laser beam are more sensitive to changes in feature height that occur at spatial distances smaller than the size of the ICESat footprints.

5 Conclusion

With an overall fundamental vertical accuracy of 2.9 meters RMSE it is concluded the EU-DEM fully meets the contractually agreed specification of 7 meters RMSE.

Looking exclusively at the region south of 60^{o}N the fundamental accuracy is 2.23 meters RMSE which is very close to the overall vertical accuracy of 2 m RMSE as initially specified in the call for tender, as opposed to the fundamental accuracy north of 60^{o}N building on complementary in-situ data sources in absence of SRTM coverage, which is assessed to 5.19 meters. Whereas the former can be concluded compliant to both contractually agreed specifications and initial tender specifications, the latter still meets the contractually agreed specifications but falls short of the original tender specifications.

For the optional, but not contracted, vertical accuracies for differentiated slope categories it is found that EU-DEM both north and south of 60^{o}N would exceed the specifications of 1 meters RMSE in lowlands (i.e. less than10% slope) and 2.5 meters RMSE in midlands (i.e.10-30% slope). For the mountains (>30% slope) the specified 5 meters RMSE would be met in the region south of 60^{o}N but not north of that boundary.

6 Recommendation

Based on the evaluation of EU-DEM vertical accuracies it is recommended that the observed difference in EU-DEM accuracies between the regions north and south of 60^{o}N is the dominating issue that need to be targeted for the planned upgrade of EU-DEM.

7 References

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APPENDIX: Specifications of the EU-DEM

The EU-DEM was requested to be produced according to a set of mandatory and optional requirements (cf. Table A.1).

Table A.1. EU-DEM mandatory and optional requirements (from CALL FOR TENDERS No ENTR/2009/27 - Implementation of an Initial GMES Service for Geospatial Reference Data Access)

	Mandatory requirements	Optional requirements
Coverage	EU27	Extended coverage of EEA38, EEA38 + international river basin districts according to the requirements as set out by the Water Framework Directive, or full wall to wall pan-European coverage
Consistency / homogeneity	Cross border consistency (countries, different data sources etc…) Consistency both with the geometry of the hydrographical pattern and Consistency with the hydrological modelling of (continuity of water flow) Water surfaces burnt in the DEM	
Resolutions	Horizontal: 1 arcsec (+/-30 m) posting (consistent with 1:100.000 scale for other (topographic) data themes); Vertical units: integer meters	Minimum variation in Z between 2 adjacent posting values should be properly described in DEM values according to following differentiation: • lowland plains: 2m (<10% slopes) ; • midlands: 5m (10 – 30 % slopes); • mountains: 10m (> 30% slopes).
Accuracies	Horizontal: better than 5 m Vertical: overall accuracy of 2 m RMSE	Vertical differentiated accuracies, corresponding with the differential resolution categories: • lowlands: 1 m absolute RMSE; • midlands: 2,5 m absolute RMSE; • mountains: 5 m absolute RMSE
Projections	WGS84, ETRS 89 and EVRF2000; geographic coordinates (Lat/Long)	the INSPIRE compliant European projection systems(LCC, LAEA, UTM) - national projections/datums

Table A.1 represent the EU-DEM specifications as set out in the Tender but the final offer for EU-DEM was accepted with the following specifications (A.2).

Table A.2. Summary of EU-DEM specifications as accepted in response to tender*.

Product	Coverage	Data Sources	Resolution	Vertical Accuracy	Access
EU-DEM	EEA38	SRTM & ASTER GDEM (+ topomaps north of 60^{o}N)	1 arc-second (~30 m)	+/- 7.0 m RMSE	Unrestricted

** Directly taken from Table 2-1 in Technical proposal by Indra. Information in brackets has been added by DHI GRAS*