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DEFENCE AND SPACE

Copernicus DEM

Copernicus Digital Elevation Model

Validation Report

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Version	Date	Chapter	Changes
1.0	09.12.2019	all	First issue
2.0	11.05.2020	3.1	Expansion of EEA39 delivery scope by Faroe Islands

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Reference Documents

[RD-01]	WorldDEM Technical Product Specification, Version 2.5, April 2019
[RD-02]	A. Gruber et al: *The TanDEM-X DEM Mosaicking: Fusion of Multiple Acquisitions Using InSAR Quality Parameters*, IEEE Journal of selected topics in applied Earth Observations and Remote Sensing, vol. 9, no. 3, March 2016
[RD-03]	C. Rossi et al: *TanDEM-X Mission: Raw DEM Generation*, 8th European Conference on Synthetic Aperture Radar, June 2010
[RD-04]	DLR Document: TD-GS-PS-0021; TanDEM-X DEM Products Specification Document, Version 3.2, 07.05.2018
[RD-05]	A. C. Brenner et al: *Precision and Accuracy of Satellite Radar and Laser Altimeter Data Over the Continental Ice Sheets*, IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 45, No. 2, February 2007
[RD-06]	C. C. Carabajal: *Aster Global DEM version 2.0 evaluation using ICESat geodetic ground control*, 2011

Applicable Documents

[AD 01]	Copernicus DEM Description Document, Version 2.0, May 2020

Uniform Resource Locators (URLs)

[URL 01]	http://maps.tnc.org/gis_data.html
[URL 02]	http://maps.tnc.org/files/metadata/TerrEcos.xml

Acronyms and Abbreviations

AD	Applicable Document
DEM	Digital Elevation Model
DLR	German Aerospace Centre
DSM	Digital Surface Model
EEA	European Environment Agency
ESA	European Space Agency
GLAS	Geoscience Laser Altimeter System
ICESat	Ice, Cloud and land Elevation Satellite
InSAR	SAR interferometer
LE	Linear Error
LiDAR	Light Detection And Ranging
NASA	National Aeronautics and Space Administration
RD	Reference Document
SAR	Synthetic Aperture Radar
URL	Uniform Resource Locator
WGS	World Geodetic System

1 Introduction

A Digital Elevation Model (DEM) is a three dimensional representation of the Earth's surface. A DEM provides elementary information for multiple applications such as landscape modelling and orthorectification. The Copernicus DEM is a global model available in 30m and 90m resolution as well as 10m for the EEA39 area.

The validation of the vertical accuracy is essential to ensure that the elevation data fulfils the specification. To perform such a validation, a suitable reference data set with a certain accuracy as well as global coverage has to be acquired.

The Geoscience Laser Altimeter System (GLAS) of NASA's Ice, Cloud and land Elevation Satellite (ICESat) has raised a unique set of data. This elevation data obtained by means of Light Detection And Ranging (LiDAR) technology provides a vertical accuracy high enough to validate the Copernicus DEM.

The objective of this document is to present the methods and implementation of statistical procedures used to validate vertical accuracy of the Copernicus DEM based on ICESat reference data.

2 Data and Methodology

2.1 Copernicus DEM

The Copernicus DEM is a Digital Surface Model (DSM) which represents the surface of the Earth including buildings, infrastructure and vegetation. This DEM is an edited DSM: identified water bodies are flattened and a consistent flow of rivers is ensured, shore- and coastlines and special features such as airports are edited. Implausible terrain structures are corrected as well [AD 01].

The Copernicus DEM is based on the WorldDEM data. The WorldDEM product is based on the radar satellite data acquired during the TanDEM-X Mission, which is funded by a Public Private Partnership between the German State, represented by the German Aerospace Centre (DLR) and Airbus Defence and Space. The operation of the satellites in orbit, the data acquisition as well as the interferometric processing of the data is performed by DLR [RD-02], [RD-03], [RD-04]. Airbus Defence and Space is refining the processed data [RD-01]. The primary goal of the mission was the generation of a worldwide, consistent, and high precision Digital Surface Model (DSM) based on Synthetic Aperture Radar (SAR) interferometry. The two satellites TerraSAR-X and TanDEM-X operated as a single-pass SAR interferometer (InSAR), using the bi-static InSAR StripMap mode. At least two complete data coverages of the Earth's surface were acquired to generate the DEM product.

The data acquisition started in December 2010 and was completed by January 2015.

2.2 ICESat GLAS Reference Data

The ICESat mission, which is part of NASA's Earth Observation program, was launched in January 2003. The Geoscience Laser Altimeter System (GLAS) on ICESat measured ice sheet changes in elevation through time, land elevations and vegetation cover, and approximate sea ice thickness.

The instrument determined the distance from the satellite to the Earth's surface and to intervening clouds and aerosols. This is done by precisely measuring the time it took for a short pulse of laser light to travel to the reflecting object and return to the satellite.

The data on the distance to the laser footprint on the surface, the position of the satellite in space as well as the pointing of the laser were all combined to calculate the elevation and position of each point measurement on the Earth.

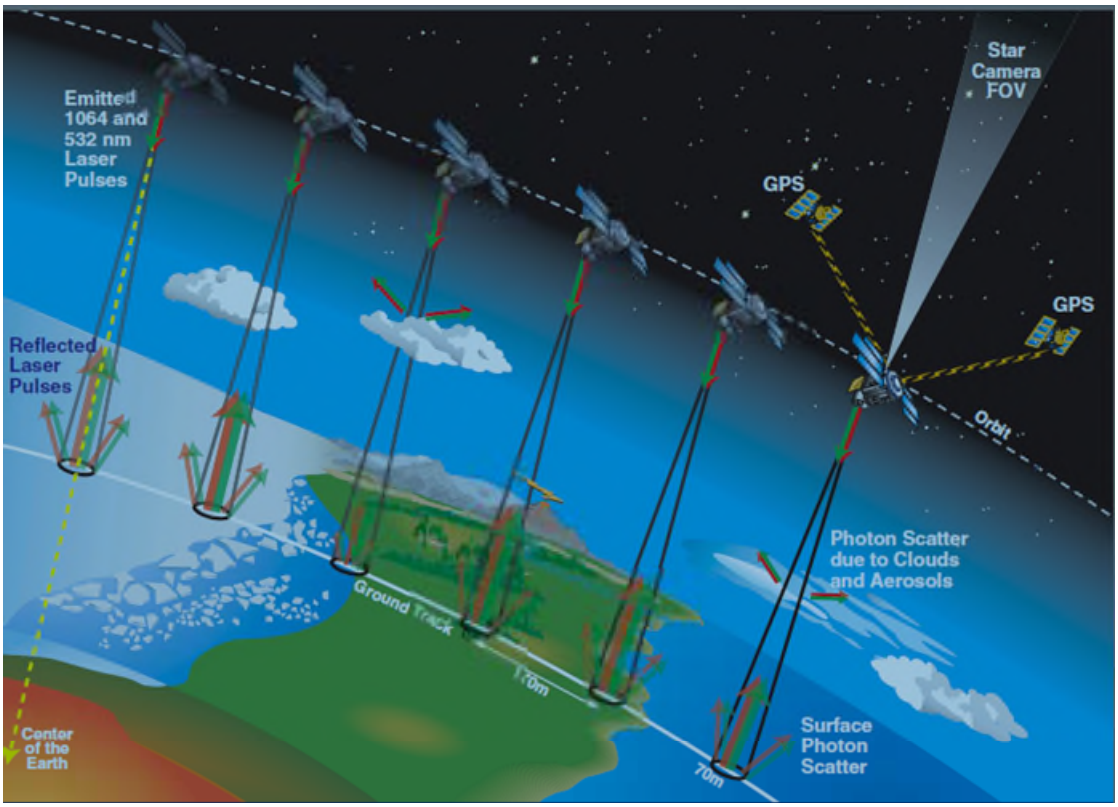

Figure 1: ICESat mission – Illustration of GLAS instrument
(Source: ICESat brochure Goddard Space Flight Center FS-2002-9-047-GSFC)

The altimetry data provides accurate and reliable reference data on a global scale. The precision of ICESat-retrieved elevations over the ice sheets as well as filtered elevations for low relief locations were validated with sub-meter accuracy [RD-05], [RD-06].

2.3 Data Comparison

In order to provide a most accurate data comparison, the ICESat elevation values have been compared with the source DEM of the Copernicus DEM, the WorldDEM at its native resolution of 0.4'' arc seconds.

To compare the ICESat GLAS v33 reference points with the same horizontal, WGS84, and the vertical reference system, EGM08, as the Copernicus DEM/WorldDEM, a transformation has been applied.

The reliability of reference height information decreases due to the presence of steep slope and/or forest or man-made structures within the ICESat GLAS footprint of approximately 50x70 meters. Therefore, a filtering procedure based on waveform attributes provided with each ICESat GLAS reference point has been developed and applied.

The footprints of ICESat GLAS reference points cover multiple resolution cells of the DEM. A distance-based average elevation of the covered DEM height values is calculated for comparison with the ICESat GLAS height value.

Since strong noise occurs in the radar signal penetrating and reflecting from a water surface, all footprints touching a water body are ignored. The Copernicus DEM Water Body Mask has been applied to filter the ICESat data respectively.

In order to eliminate ICESat points collected in mountainous terrain, a standard deviation filter has been applied.

Considering the footprint of the ICESat data, not only one DEM pixel, but the respective pixels covering the footprint are taken into account.

The statistics are determined per each 1°x1° degree cell. ICESat data close to the edge of a cell was eliminated to ensure a valid application for all kernel operations.

An example on filtered ICESat data is shown for the region around Lake Garda in Northern Italy in Figure 2.

The radar signal penetration of TerraSAR-X and TanDEM-X into dry firm snow prevents a direct comparison with ICESat GLAS data which represents a signal reflection at the top surface of dry firm snow. Additionally, the ICESat GLAS reference point data was acquired between 2003 and 2009 whereas the TanDEM-X/WorldDEM has been acquired between December 2010 and January 2015. There is therefore a temporal decorrelation of the two datasets and potential elevation changes of the areas with permanent snow/ice cover (e.g. seasonal variation within a 1-year timeframe; decrease of the ice shield over the years 2003 to 2015) which would affect the accuracy statistics of the TanDEM-X/WorldDEM data. Hence the statistics are separated into areas with and without permanent snow/ice cover. A valid accuracy statistic is only available for areas without permanent snow/ice cover, while for regions of permanent snow/ice cover the absolute vertical difference between both datasets is assessed.

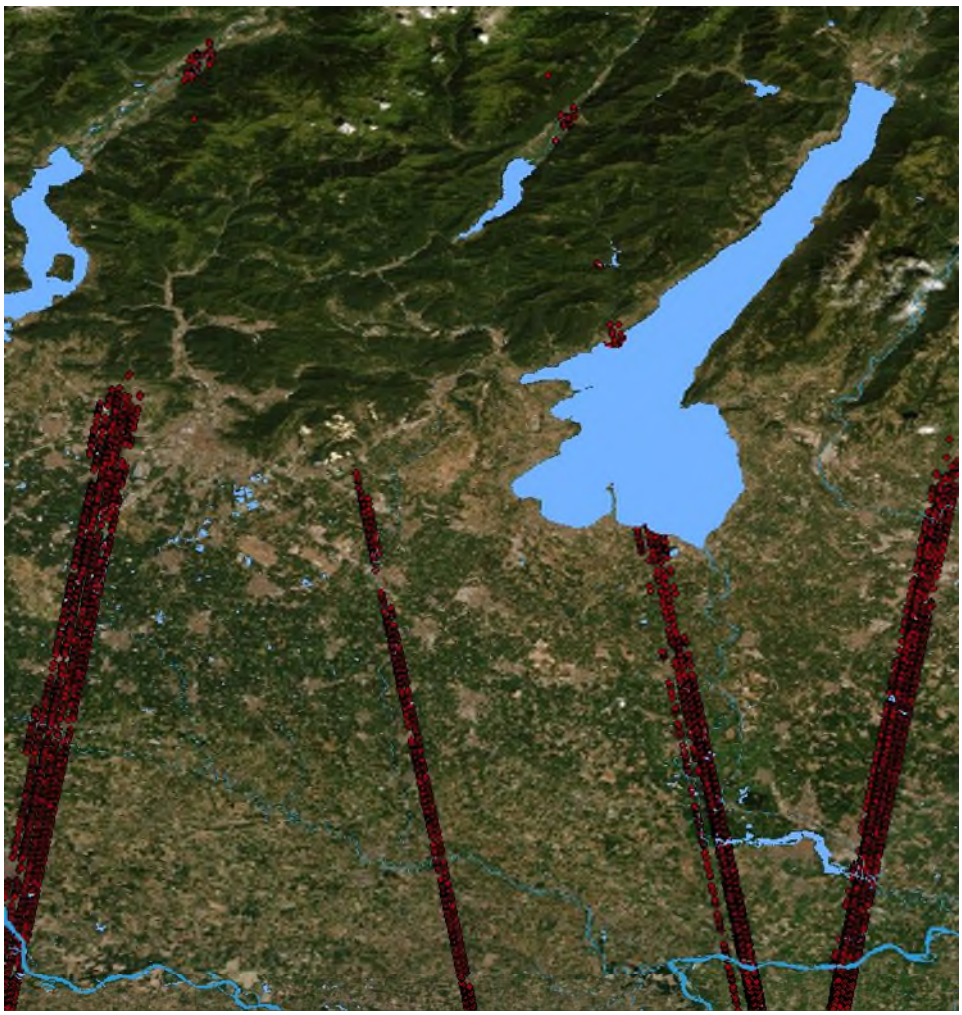

Figure 2: Image of filtered ICESat data (red points) – Lake Garda Northern Italy (Source: Esri World Imagery Basemap)

2.4 WWF Ecoregion

To analyse the statistical results in respect to the ecological regions of the Earth, each geocell has been classified according to World Wildlife Fund (WWF) Terrestrial Ecoregions

The WWF terrestrial Ecoregions consist of 14 Major Habitat Types, which reflect the diverse array of organisms adapted to life on land. These habitats range from the wettest of forest types to the driest and hottest desert conditions. Figure 3 shows the distribution of the Terrestrial Ecoregions.

For the classification of the ecoregion per cell, the Terrestrial Ecoregions layer of the Nature Conservancy has been applied [URL 01]. Detailed information regarding the metadata of the ancillary data set can be found in [URL 02]. For all 1°x1° degree cells of the EEA39 coverage, one ecoregion has been assigned depending on the dominant realm.

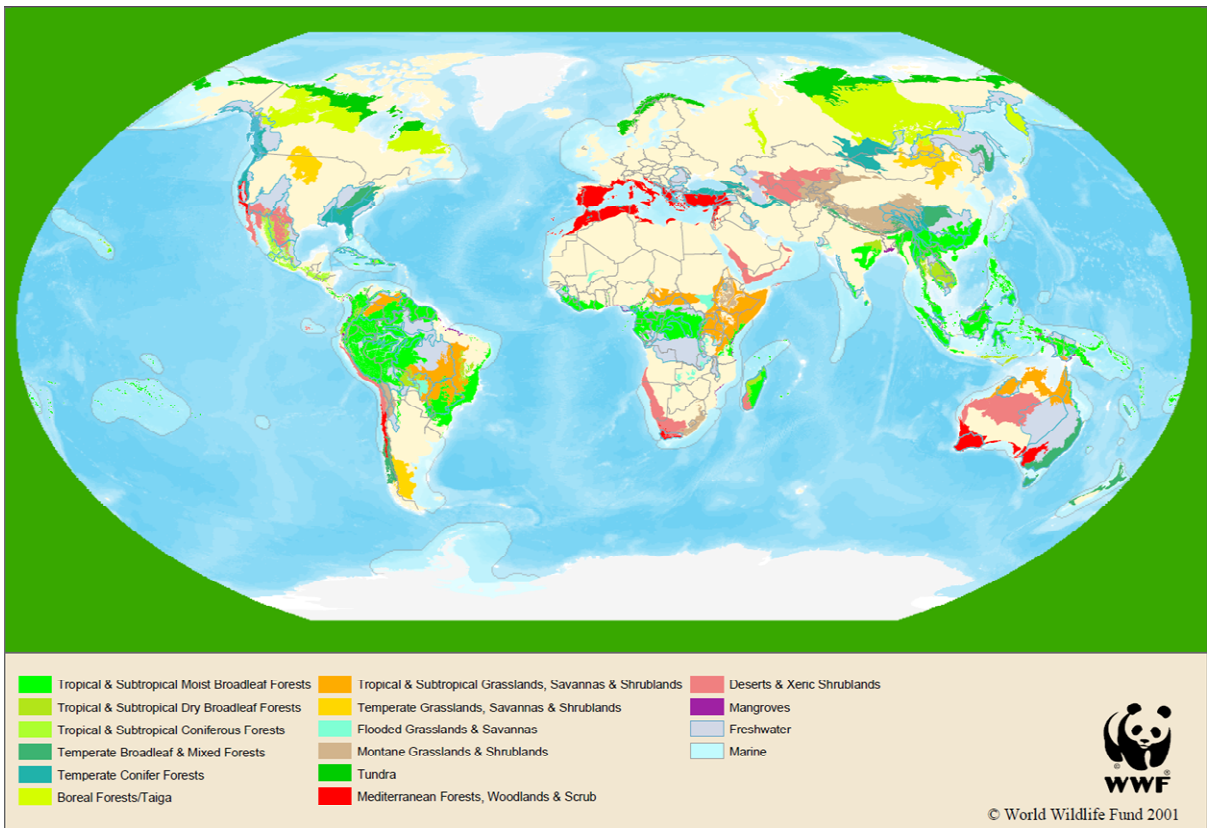

Figure 3: WWF Terrestrial Ecoregions

2.5 Statistical Validation

In the following section, the statistical validation methods for the accuracy assessment of the Copernicus DEM are described.

2.5.1 Reference Data

The validity of the accuracy assessment is highly dependent on the reference data. Since it cannot be ensured that the reference data is error-free, the criterion for a trustworthy validation is to use reference data with a three times higher accuracy measure than the expected accuracy of the DEM product being assessed.

The mission goal of TerraSAR-X and TanDEM-X was the generation of a global DEM with an accuracy better than 10m. After quality filtering the ICESat data provides sub-meter accuracies and therefore is an adequate reference for the Copernicus DEM. The accuracy measure for ICESat GLAS is stated as less than one meter [RD-05].

To ensure a robust accuracy value per 1°x1° cell, only cells with at least 200 valid ICESat reference points are considered for the accuracy assessment.

2.5.2 Accuracy Metrics

After applying multiple filtering operations as described in section 2.3 to ensure that only reliable reference points are considered, the following accuracy measures are determined per 1°x1° cell.

Number of samples	n
Absolute Vertical Accuracy Linear Error at 90% confidence interval (LE_{90})	$D = sorted(\lvert\Delta h\rvert)$ $P = 90$ $N = int[\left(\frac{P}{100}\right) * n]$ $LE_{90} = D(N)$
Absolute Vertical Accuracy Linear Error at 68% confidence interval (LE_{68})	$D = sorted(\lvert\Delta h\rvert)$ $P = 68$ $N = int[\left(\frac{P}{100}\right) * n]$ $LE_{68} = D(N)$
Mean Error	$\hat{u} = \frac{1}{n}\sum_{i=1}^{n}\Delta h_i$
Standard Deviation	$\hat{\sigma} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta h_i - \hat{u})^2}$
Root Mean Square Error (RMSE)	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\Delta h_i{}^2}$
Vertical Error	$\Delta h = DEM_Z - ICESat_Z$
Threshold for Outliers	$\lvert\Delta h\rvert \geq 20$

3 Results

3.1 EEA39 Analysis

3.1.1 Scope

The DEM data covers 1,180 geocells with an extent of 1°x1°. An overview of all geocells provided is shown in the figure below.

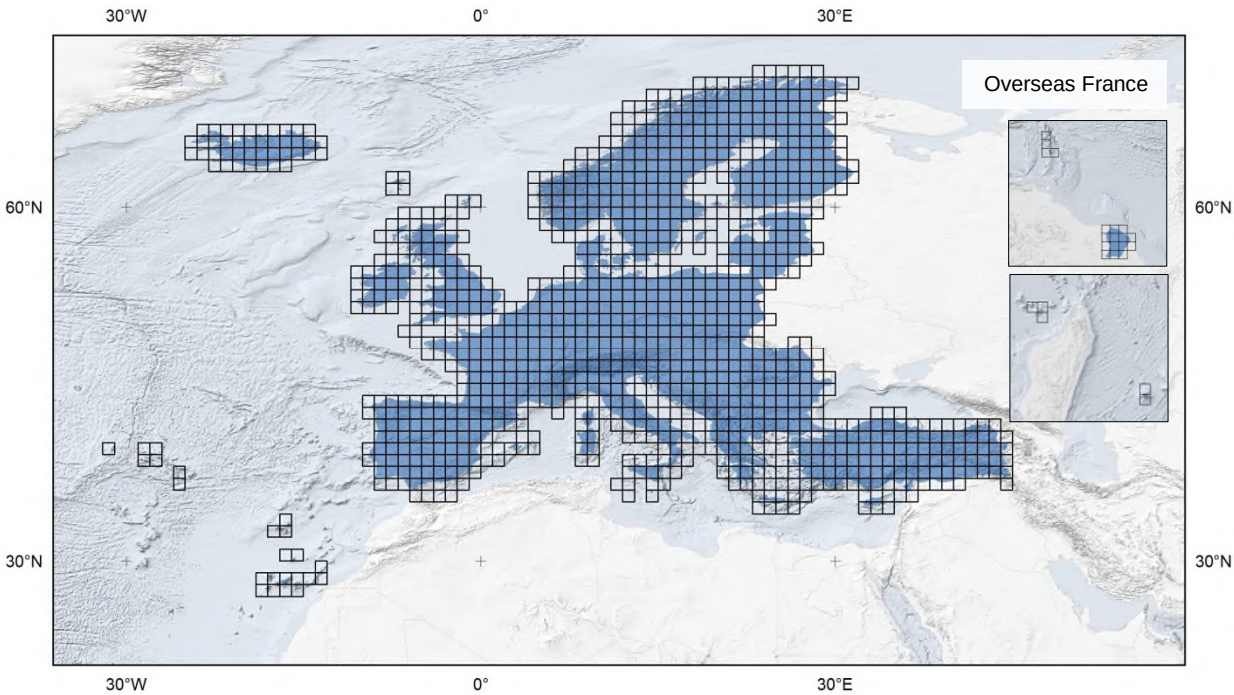

Figure 4: Coverage of all 1,180 geocells comprising the area of the EEA39 region

3.1.2 Accuracy Results

In the following section, the results of the accuracy assessment of the Copernicus DEM for the EEA39 region are described.

The table below summarizes the accuracy values. All statistical results provided in the section take into account only cells with at least 200 valid ICESat points. Considering about 2.7million valid ICESat points, the absolute vertical accuracy at 90% (LE_{90}) confidence level indicates an accuracy of 2.03m. The assessment results in a mean error of -1.34 meters and a standard deviation of 0.83m. Figure 5 shows the spatial distribution of the geocells with respect to their absolute vertical accuracy. The blank cells indicate cells with insufficient ICESat reference points. The cells with an accuracy value between 2 and 5 m are clustered along the mountainous terrain of Norway as well as the forest covered areas of Finland. Iceland shows low accuracy values due to its rough terrain as well as seasonal snow and ice cover.

According to the histogram in Figure 6, more than 70% of all geocells have an absolute vertical accuracy value better than 2 meters. Only 1% of cells have an accuracy value worse than 5 meters.

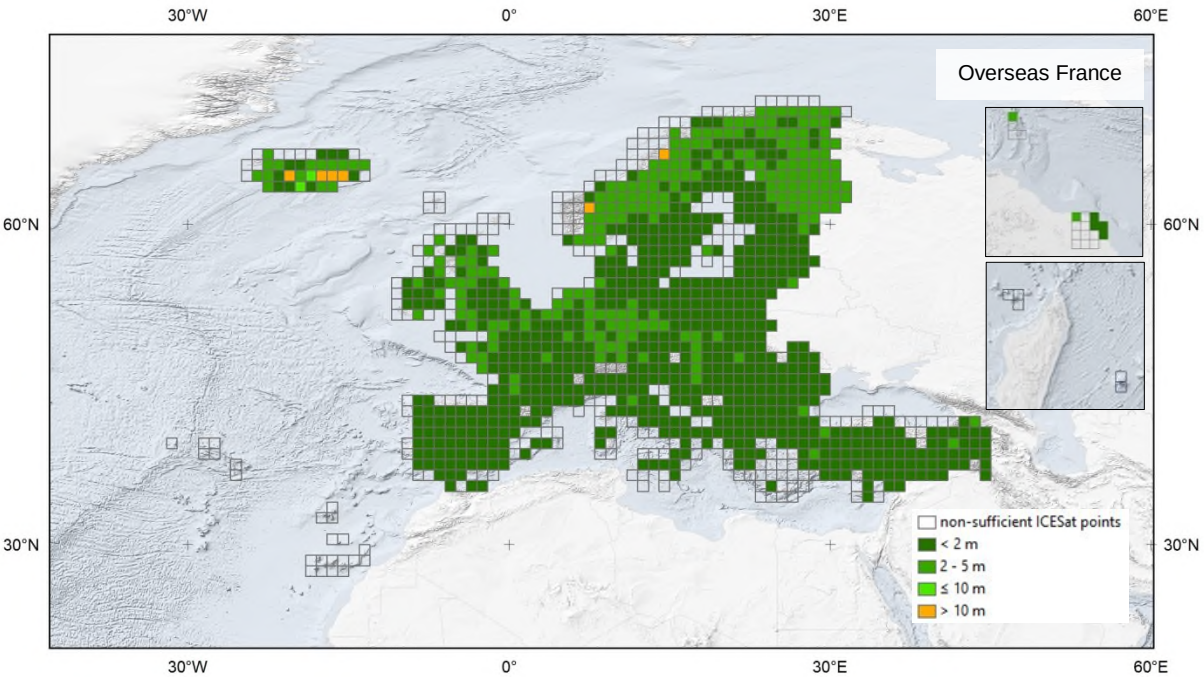

Figure 5: Coverage of geocells comprising the area of the EEA39 region classified according to statistical LE90 value per cell in meter

Table 1: Copernicus DEM Accuracy Results – EEA39 area

	No. of 1°x1° cells	No. of valid ICESat points	LE_{68} [m]	LE_{90}[m]	Mean error $\hat{u}$ [m]	St. dev $\hat{\sigma}$ [m]	RMSE [m]
EEA39	**909**	**2,768,916**	**1.64**	**2.03**	**-1.34**	**0.83**	**1.63**

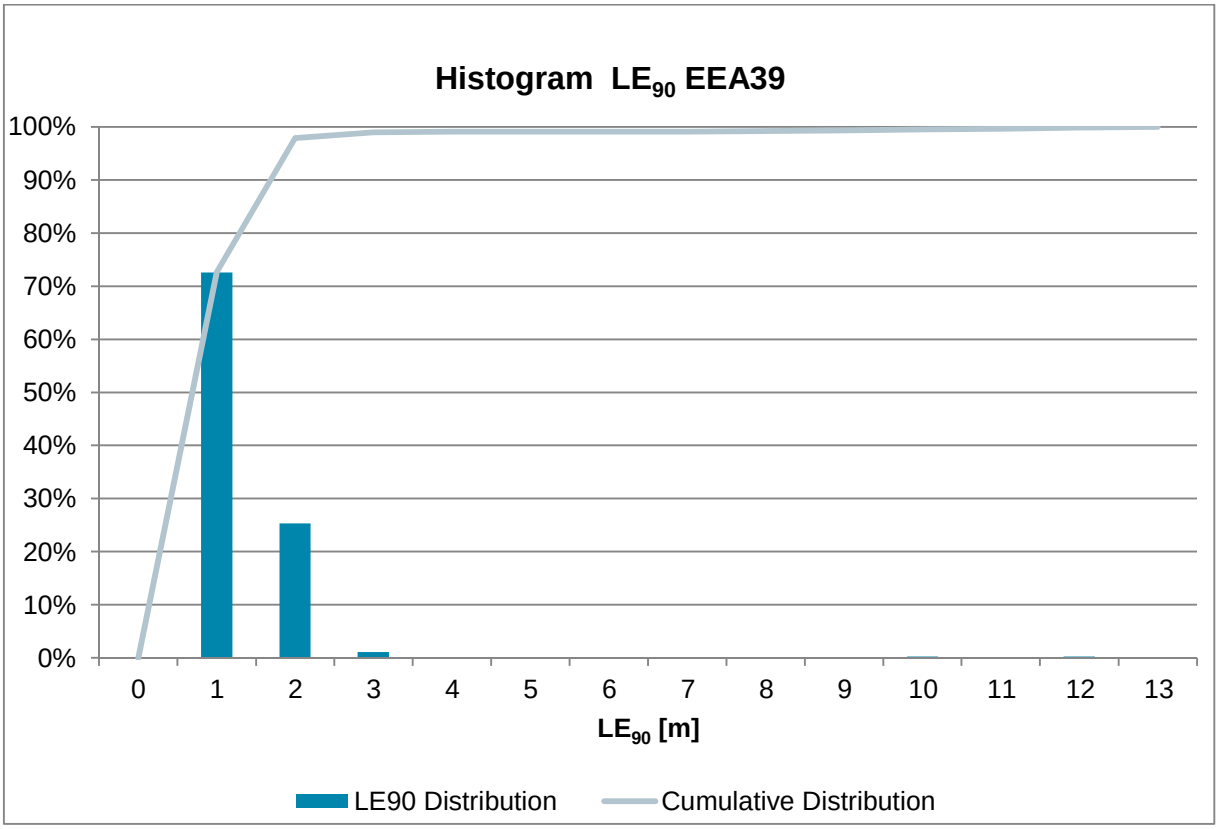

Figure 6: Histogram of the LE_{90} distribution of the EEA39 area. The bins represent half open intervals, e.g. bin 2 includes all $2 \leq LE_{90} < 3$ values.

Ecoregion

Table 2 indicates the accuracy assessment of the EEA39 region with respect to the WWF Ecoregions. The majority of regions such as *Mediterranean Forests* and *Temperate Conifer Forests* indicate an accuracy level better than 2 meter absolute vertical accuracy. *Tundra* and *Boreal Forests* show the lowest accuracy value compared to other regions. The Tundra regions of EE39 are mostly located in Norway, which is known as overall steep terrain and would explain a slightly poorer LE_{90} value, correlating with the accuracy distribution shown in Figure 5. The results give a clear indication of a divergent accuracy level in ice-covered regions, as noted in Chapter 2.3.

Table 2: Accuracy assessment of the Copernicus DEM for the EEA39 region in respect to the WWF Ecoregion

WWF Ecoregion	No. of 1°x1° cells	No. of valid ICESat points	LE_{68} [m]	LE_{90}[m]	Mean error $\hat{u}$ [m]	St. dev $\hat{\sigma}$ [m]	RMSE [m]
Boreal Forests/Taiga	174	419,741	1.70	**2.33**	-1.22	1.11	1.70
Inland Water	1	205	2.27	**2.70**	-1.67	1.41	2.18
Mediterranean Forests, Woodlands and Scrub	168	492,280	1.53	**1.79**	-1.33	0.51	1.43
Rock and Ice	2	9,830	7.43	**11.82**	-4.93	4.80	6.90
Temperate Broadleaf and Mixed Forests	450	1,586,511	1.61	**1.91**	-1.34	0.83	1.62
Temperate Conifer Forests	40	48,360	1.57	**1.84**	-1.36	0.59	1.50
Temperate Grasslands, Savannas and Shrublands	20	137,834	1.60	**1.87**	-1.44	0.44	1.51
Tropical and Subtropical Moist Broadleaf Forests	6	5,700	1.57	**1.93**	-1.09	1.41	1.82
Tundra	48	68,455	1.91	**2.76**	-1.61	1.14	2.02

3.2 Global Analysis

3.2.1 Scope

The Copernicus DEM data covers in total 26,470 geocells with an extent of 1°x1°. The accuracy assessment is split into two parts, since the ice-covered regions have to be treated differently. Therefore, in total 18,561 cells are considered for the global assessment of non-ice-covered regions.

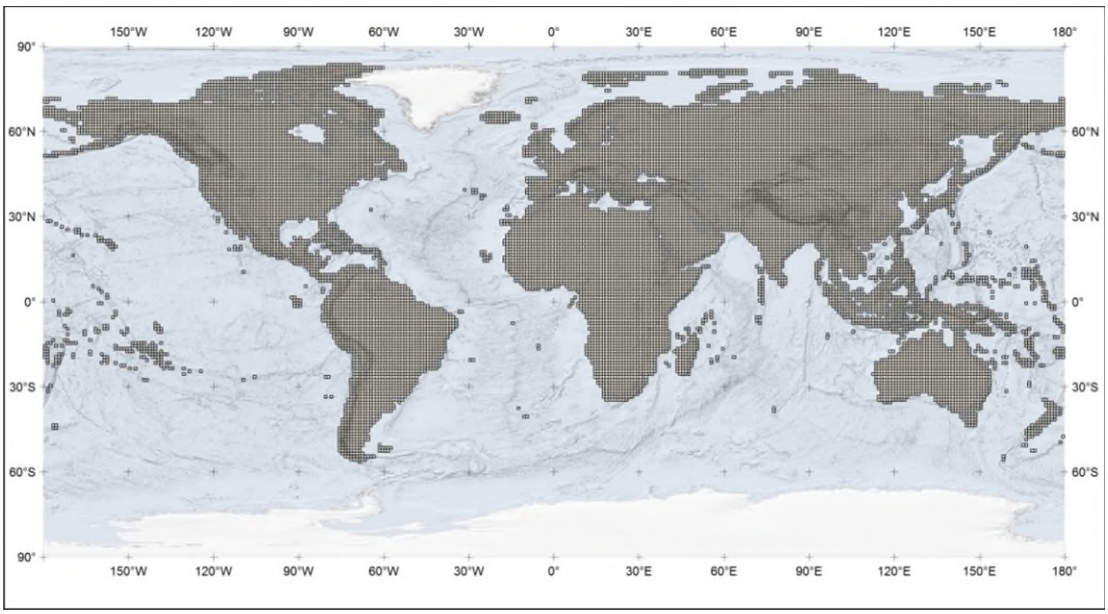

Figure 7: Coverage of all 18,561 geocells considered in the accuracy assessment of the global Copernicus DEM data set

3.2.2 Global Accuracy Results

In the following section, the results of the accuracy assessment of the global Copernicus DEM are summarized. Since the accuracy results of Greenland and Antarctica should be treated with caution due to their ice coverage, the results are removed from the global statistics.

The table below summarizes the accuracy values. Only cells with at least 200 valid ICESat points are incorporated in the evaluation. Considering about 11 million valid ICESat points, the absolute vertical accuracy at 90% (LE_{90}) confidence level is 2.17m. The assessment results in a mean error of -1.29 meters and a standard deviation of 0.85m. Figure 8 shows the spatial distribution of the geocells with respect to their absolute vertical accuracy. The blank cells refer to cells with insufficient ICESat reference points. The cells with an accuracy value between 2 and 5 m are clustered along mountainous terrain as well as forest covered areas such as Taiga and Tundra. The West coast of Canada indicates low accuracy values due to its rough terrain.

According to the histogram in Figure 9, almost 95% of all geocells have an absolute vertical accuracy value better than 3 meters. Around 2% of cells have an accuracy value worse than 5 meters.

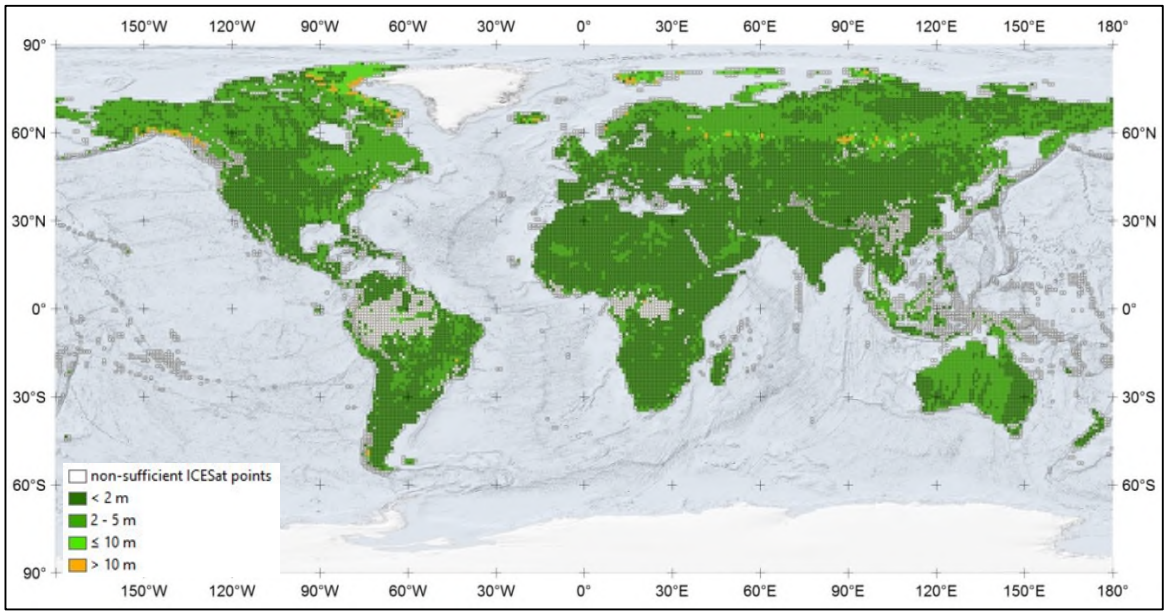

Figure 8: Global coverage of geocells classified according to statistical LE90 value per cell in meter

Table 3: Copernicus DEM Accuracy Results

Area	No. of 1°x1° cells	No. of valid ICESat points	LE_{68} [m]	LE_{90}[m]	Mean error $\hat{u}$ [m]	St. dev $\hat{\sigma}$ [m]	RMSE [m]
Global	**15,050**	**111,364,047**	**1.69**	**2.17**	**-1.29**	**0.85**	**1.68**

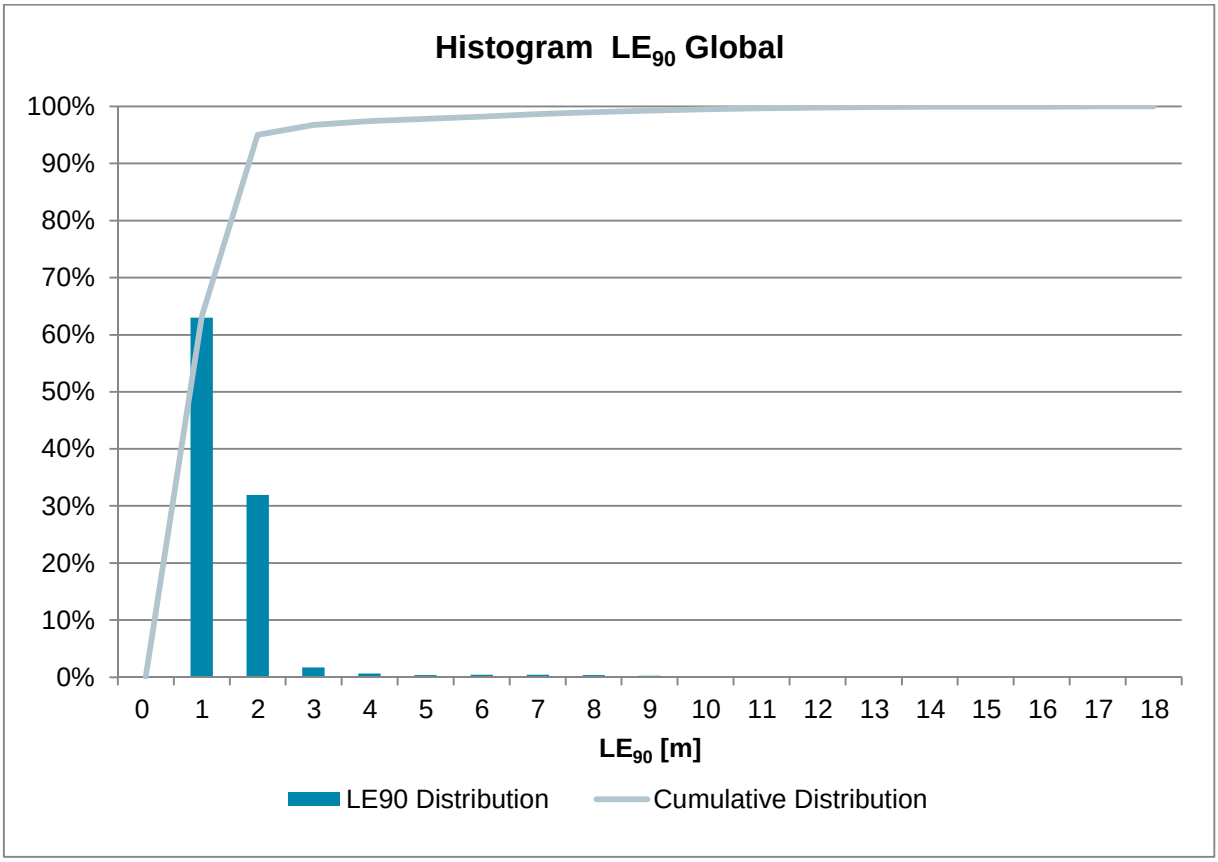

Figure 9: Histogram of the global LE90 distribution. The bins represent half open intervals, e.g. bin 2 includes all $2 \leq LE_{90} < 3$ values.

Ecoregion

Table 4 indicates the accuracy assessment in respect to the WWF Ecoregions. The majority of regions such as *Deserts and Xeric Shrublands* and *Flooded Grasslands and Savannas* indicate an accuracy level better than 2 meter absolute vertical accuracy. *Tundra*, *Boreal Forests* and *Temperate Conifer Forests* show the lowest accuracy value compared to other regions. These regions are mostly covered by conifer trees, where the penetration depth of the X-Band radar deviates from GLAS LiDAR and a lower accuracy value is expected. The results give a clear indication of a divergent accuracy level in ice regions as noted in 2.3.

Table 4: Accuracy assessment of the Copernicus DEM for the Copernicus DEM in respect to the WWF Ecoregion

WWF Ecoregion	No. of 1°x1° cells	No. of valid ICESat points	LE_{68} [m]	LE_{90}[m]	Mean error $\hat{\mu}$ [m]	St. dev $\hat{\sigma}$ [m]	RMSE [m]
Boreal Forests/Taiga	2737	13,085,932	1.70	**2.45**	-0.86	1.37	1.81
Deserts and Xeric Shrublands	2786	40,320,619	1.60	**1.85**	-1.45	0.38	1.51
Flooded Grasslands and Savannas	83	977,261	1.53	**1.83**	-1.21	0.72	1.44
Inland Water	37	147,141	1.66	**2.03**	-1.16	0.72	1.57
Mangroves	30	49,996	1.46	**1.96**	-0.83	0.97	1.42
Mediterranean Forests, Woodlands and Scrub	405	2,402,032	1.58	**1.84**	-1.37	0.51	1.48
Montane Grasslands and Shrublands	438	1,686,911	1.58	**1.87**	-1.43	0.48	1.53
Rock and Ice	3	11,509	10.55	**14.14**	-7.90	4.85	9.50
Temperate Broadleaf and Mixed Forests	1,504	5,638,950	1.62	**2.00**	-1.22	1.07	1.74
Temperate Conifer Forests	386	836,551	2.07	**2.80**	-1.43	1.37	2.16
Temperate Grasslands, Savannas and Shrublands	1,136	12,708,129	1.55	**1.81**	-1.37	0.48	1.48
Tropical and Subtropical Coniferous Forests	49	96,710	1.54	**1.83**	-1.26	0.63	1.43
Tropical and Subtropical Dry Broadleaf Forests	359	2,002,915	1.51	**1.89**	-1.09	0.83	1.45
Tropical and Subtropical Grasslands, Savannas and Shrublands	1,693	15,901,473	1.50	**1.86**	-1.10	0.72	1.41
Tropical and Subtropical Moist Broadleaf Forests	1,114	2,710,889	1.58	**2.09**	-1.07	1.06	1.63
Tundra	2,290	12,787,029	2.07	**2.83**	-1.80	0.87	2.04

3.2.3 Greenland and Antarctica Absolute Difference Results

In the following section the results of the regions with permanent ice cover are summarized. As explained in 2.3, the radar signal penetration of TerraSAR-X and TanDEM-X into dry firm snow prevents a direct comparison with ICESat GLAS data which represents a signal reflection at the top surface of dry firm snow. Hence the absolute difference assessment is included in this report for the sake of completeness rather than providing a valid accuracy assessment of the Copernicus DEM data in these regions.

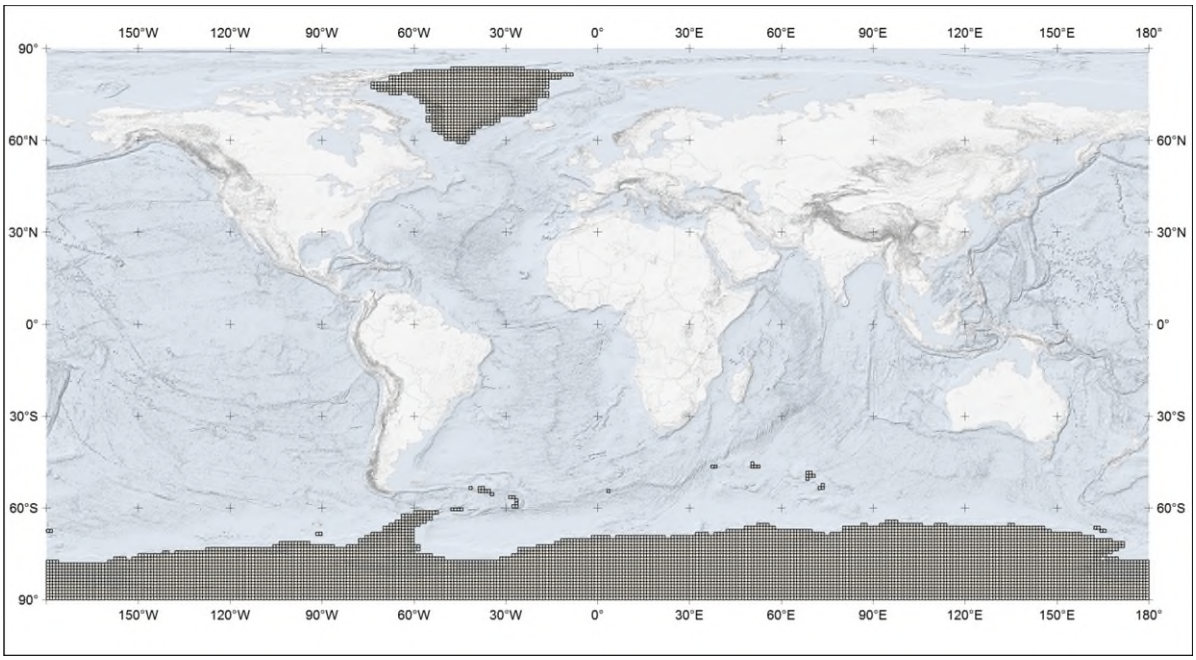

Figure 10: Coverage of all geocell comprising Greenland and Antarctica region

The difference values are summarized in Table 5. As expected, the absolute vertical difference deviates widely from the global accuracy values. With an average value of more than 6 meters, the LE_{90} is three times higher than the global assessment. Figure 11 shows the spatial distribution of the geocells with respect to their absolute vertical difference. The blank cells refer to cells with insufficient ICESat reference points.

The histogram of the absolute accuracy shows that about 20% of the all cells have a value below 5 meters. The cell's difference aggregates between 5 to 8 meters.

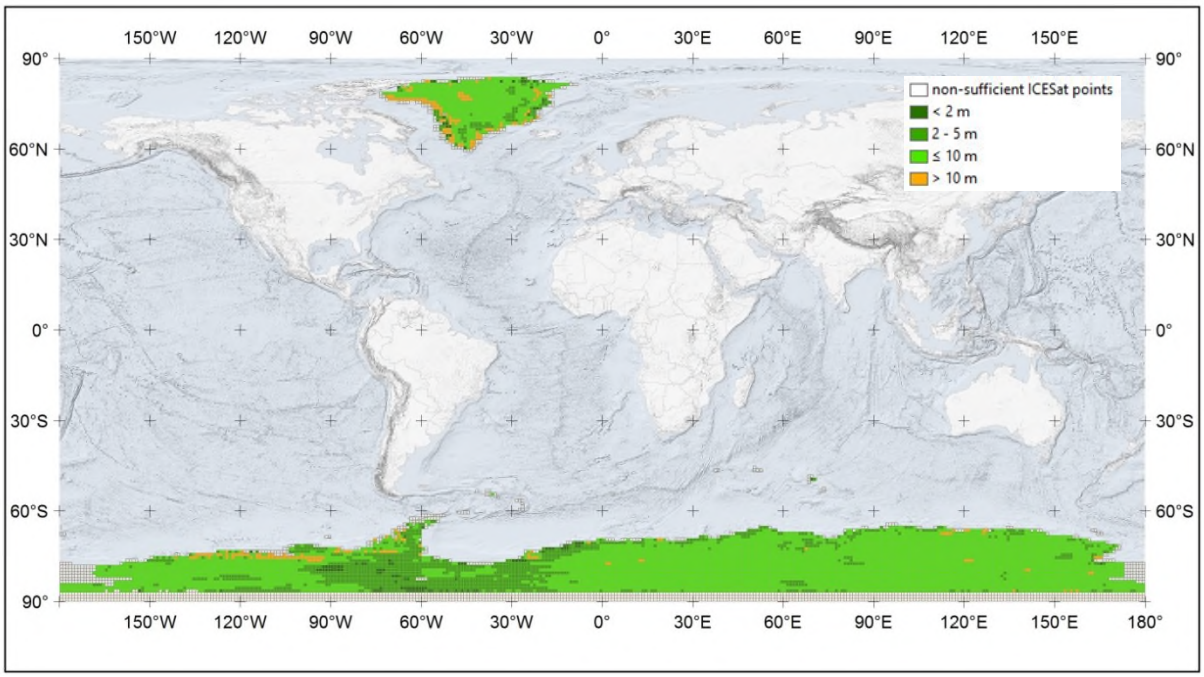

Figure 11: Coverage of Antarctica and Greenland geocells classified according to statistical LE90 value per cell in meter

Table 5: Copernicus DEM Absolute Difference Results for Greenland and Antarctica

Area	No. of 1°x1° cells	No. of valid ICESat points	LE_{68} [m]	LE_{90}[m]	Mean error $\hat{u}$ [m]	St. dev $\hat{\sigma}$ [m]	RMSE [m]
Greenland	746	7,859,932	5.94	**7.26**	-5.36	1.55	5.73
Antarctica	5623	64,950,624	5.29	**6.38**	-4.74	1.36	5.07

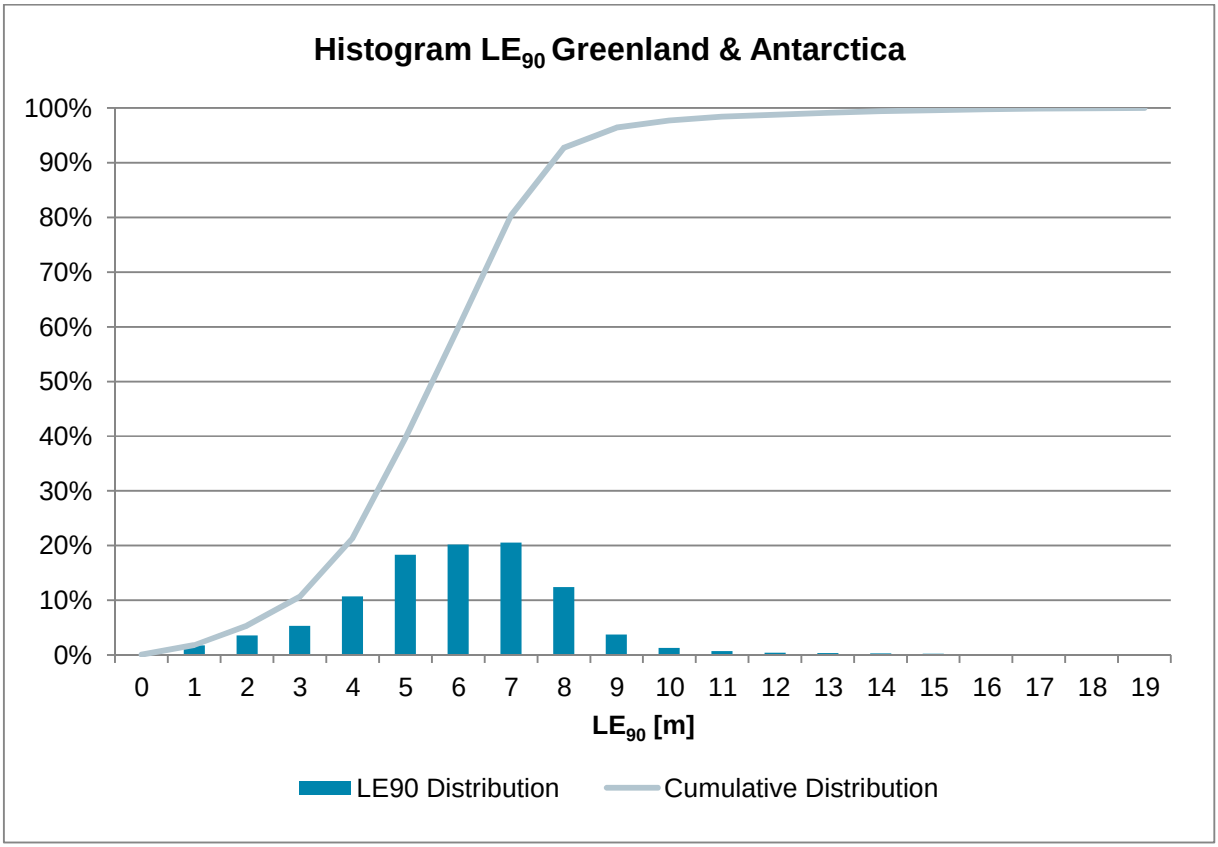

Figure 12: Histogram of LE90 distribution of Antarctica and Greenland region. The bins represent half open intervals, e.g. bin 2 includes all 2 ≤ LE_{90} < 3 values.

Ecoregion

When classifying the geocells covering Greenland and Antarctica according to the WWF terrestrial Ecoregions, the cells are distinguished between *Rock and Ice* and *Tundra.* The treeless polar desert i.e. Tundra shows a slightly better difference value than the snow and ice covered regions. Due to frequent snow cover along these high latitudes the absolute vertical accuracy of the Tundra deviates from the accuracy value of the Tundra region within lower latitudes.

Table 6: Accuracy assessment of the Copernicus DEM for Greenland and Antarctica in respect to the WWF Ecoregion

WWF Ecoregion	No. of 1°x1° cells	No. of valid ICESat points	LE_{68} [m]	LE_{90}[m]	Mean error $\hat{u}$ [m]	St. dev $\hat{\sigma}$ [m]	RMSE [m]
Rock and Ice	4,402	53,530,744	5.75	6.71	-5.29	1.19	5.50
Tundra	1,967	19,279,812	4.51	5.96	-3.74	1.80	4.37

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