Performance evaluation of Sentinel-1 derived DEMs using Copernicus DEM and ICESat-2

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Motivation

The capabilities of repeat-pass interferometry to derive DEMs from Sentinel-1 (S1) imagery are limited by coherence as well as vegetation coverage and slope among others.

Quality and accuracy evaluation of several Sentinel-1 derived DEMs is performed by using ICESat-2 ATL08, Copernicus (COP) DEM and Lidar as reference data.

The main focus of this study is

- the correct processing and application of various parameter filter techniques of ICESat-2 data to provide accurate height reference data and
- the evaluation of SAR-derived DEM quality in consideration of different land cover types and topographic conditions.

Test sites and data

South Africa | Cape Town	
S1 DEM (5x20m):	03.03.2019 and 15.03.2019 ascending
Lidar DTM (10m):	2011 – 2015
COP DEM (30m):	2010 – 2014
ICESat-2 ATL08 (12x100m):	10/2018 – 12/2021 34.892 data points

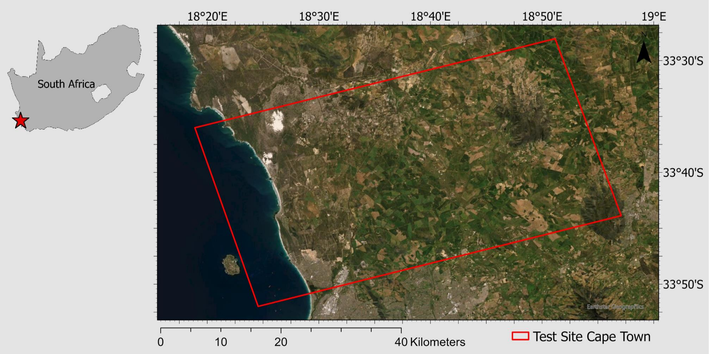

Table 1: Cape Town | DEM - ICESat-2 difference statistics

	CANOPY (m)			TERRAIN (m)		
	S1 (5x20m)	COP (30m)	Lidar DTM (10m)	S1 (5x20m)	COP (30m)	Lidar DTM (10m)
Count	11.015	7.277	5.360	31.995	20.905	17.118
Mean	3,17	-2,65	-3,23	2,49	-0,09	-0,15
Median	1,92	-2,56	-2,70	3,13	-0,30	-0,18
StdDev	**51,02**	**3,29**	**2,88**	**45,99**	**1,83**	**1,05**
Min	-184,05	-33,53	-42,24	-184,20	-30,31	-26,95
Max	205,66	38,78	35,78	207,16	44,34	41,34

Germany | Eifel	
S1 DEM (5x20m):	27.12.2017 and 02.01.2018 descending
Lidar DSM/DTM (1m):	02/ – 04/2016
COP DEM (30m):	2010 – 2014
ICESat-2 ATL08 (12x100m):	10/2018 – 12/2021 16.354 data points

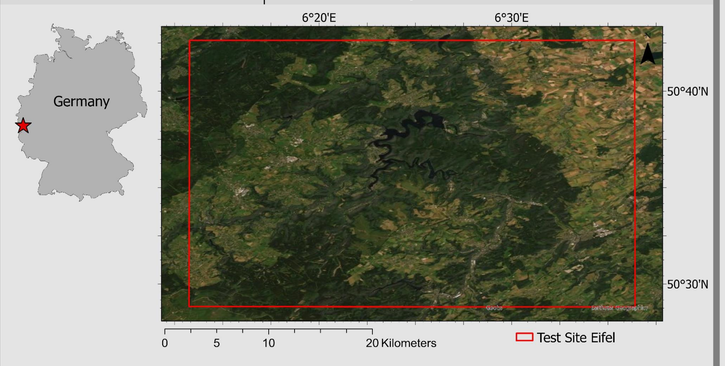

Table 2: Eifel | DEM - ICESat-2 difference statistics

	CANOPY (m)			TERRAIN (m)		
	S1 (5x20m)	COP (30m)	Lidar DSM (1m)	S1 (5x20m)	COP (30m)	Lidar DTM (1m)
Count	3.911	2.831	3.578	4.322	3.103	3.960
Mean	9,47	-1,98	-0,55	12,31	0,20	-0,11
Median	8,76	-2,49	-1,27	13,25	-0,06	-0,11
StdDev	**24,58**	**5,85**	**4,20**	**15,53**	**2,04**	**0,88**
Min	-139,81	-37,29	-28,10	-50,71	-12,03	-8,57
Max	121,26	40,55	24,93	123,20	17,10	14,56

Germany | Münsterland	
S1 DEM (5x20m):	09.09.2018 and 03.02.2020 descending
Lidar DSM/DTM (1m):	November – April, 2015 – 2021
COP DEM (30m):	2010 – 2014
ICESat-2 ATL08 (12x100m):	10/2018 – 12/2021 105.640 data points

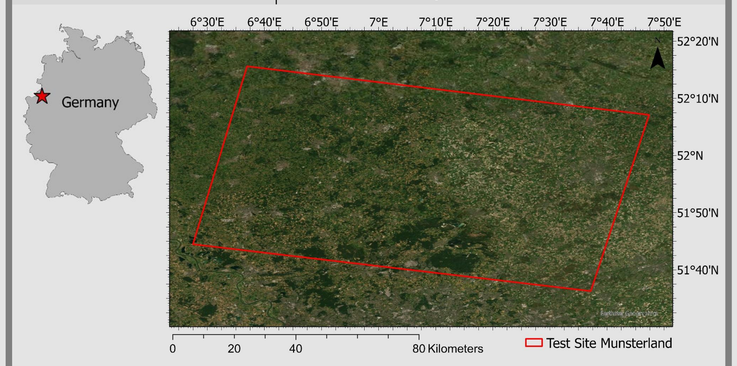

Table 3: Münsterland | DEM - ICESat-2 difference statistics

	CANOPY (m)			TERRAIN (m)		
	S1 (5x20m)	COP (30m)	Lidar DSM (1m)	S1 (5x20m)	COP (30m)	Lidar DTM (1m)
Count	47.037	36.697	3.391	70.837	55.463	5.798
Mean	-5,95	-3,03	-1,52	-0,96	0,68	1,37
Median	-5,83	-2,66	-1,40	-1,09	0,22	0,29
StdDev	**9,48**	**4,80**	**3,87**	**8,29**	**2,26**	**2,47**
Min	-121,88	-114,38	-20,39	-45,95	-21,77	-18,43
Max	53,69	52,34	33,48	79,65	78,30	29,30

Cape Town – DEM differences

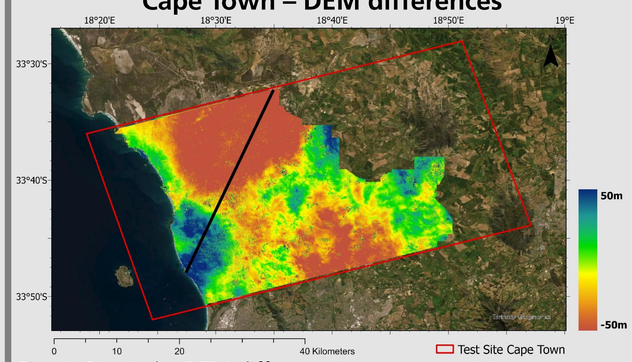

Fig. 1: S1 – Lidar DTM difference image

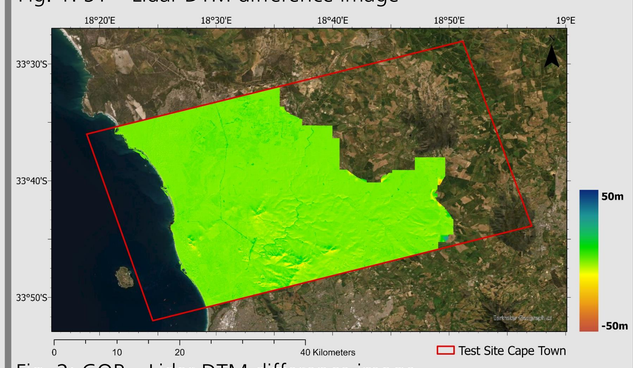

Fig. 2: COP – Lidar DTM difference image

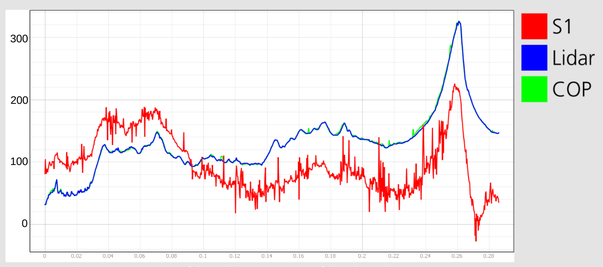

Fig. 3: Elevation profile (Fig. 1 profile line)

Eifel – DEM differences

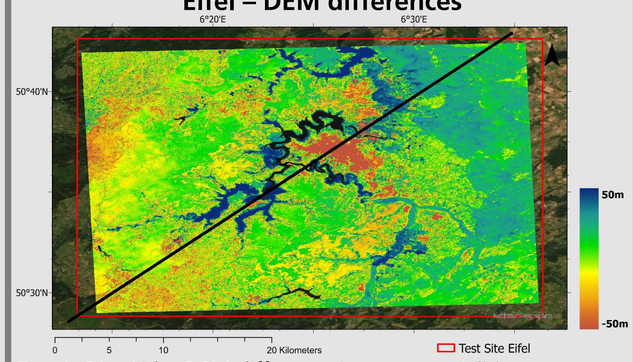

Fig. 4: S1 – Lidar DSM difference image

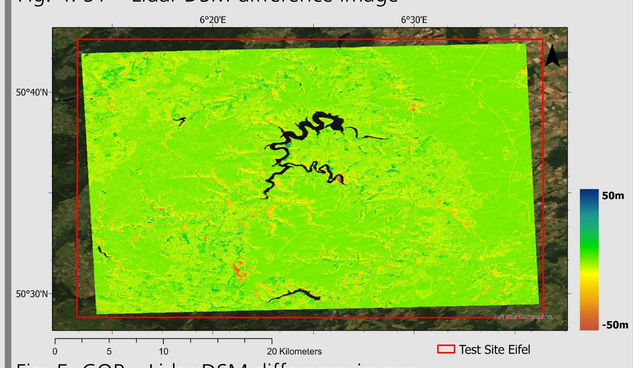

Fig. 5: COP – Lidar DSM difference image

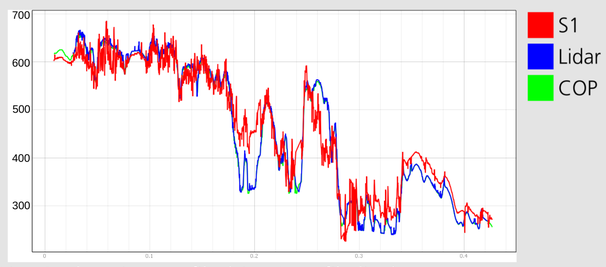

Fig. 6: Elevation profile (Fig. 4 profile line)

Münsterland – DEM differences

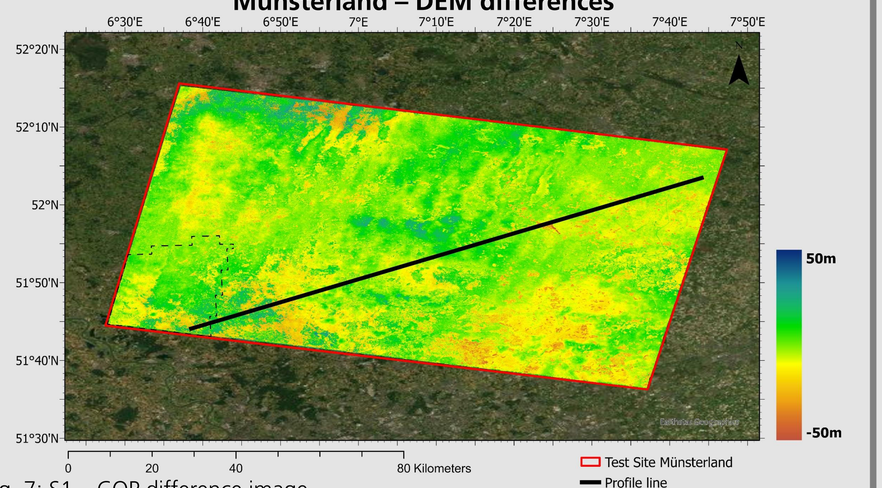

Fig. 7: S1 – COP difference image

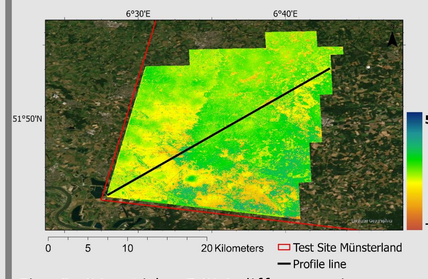

Fig. 8: S1 – Lidar DSM difference image

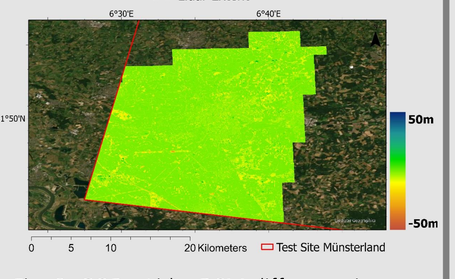

Fig. 9: COP – Lidar DSM difference image

Fig. 10: Elevation profile (Fig. 7 profile line)

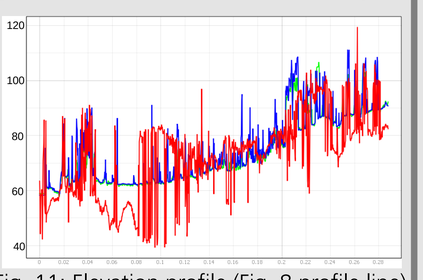

Fig. 11: Elevation profile (Fig. 8 profile line)

Discussion

With the applied filter parameter, ICESat-2 elevation segments achieve good accuracies of around 1-2m standard deviation for terrain heights and 3-4 m for canopy heights compared to Lidar. The filters applied leave only reliable data points while still maintaining adequate coverage of reference data at the test sites.

S1 performance varies in all test sites due to different reasons:

- Due to flat relief and lack of dense forests, Münsterland shows the best performance despite atmospheric disturbances in form of waves originating from the S1 DEM (see. Fig. 7). Fig. 11 shows high scattering of S1 height values over agricultural and urban areas due to the applied processing methods of S1 data products and confounding factors in S1 DEM derivation.
- Despite similar conditions in landscape and slope, Cape Town performs poorly as the S1 DEM shows great height differences. Unwrapping errors result in over- and underestimation of large parts at the test site, underlining that processing methods and coherence are just as important as good landscape conditions.
- Eifel visualizes the great impact of steep slopes as well as extensive and dense vegetation coverage on S1 DEM performance. The elevation profile (see Fig. 6) shows the high scattering of S1 height values above forests slowly declining until almost nonexistent over agricultural areas. The difference image (see Fig. 4) outlines the underestimation of dense forests and overestimation of steep slopes in the S1 DEM.

Processing

- Synthetic aperture radar interferometry (InSAR) | Repeat-pass interferometry:
  1. Combination of two complex phase products to an interferogram.
  2. Calculation of the coherence image and phase unwrapping.
  3. Geocoding of the unwrapped phase and translation into a geophysical unit.
  4. Spatial reference (ellipsoid, coordinate system) and resampling to a uniform pixel spacing.
- DEM and ICESat-2 difference statistics for ATL08 land segments (12x100m):
  - Filters: quality flag, uncertainty<10m, COP land cover classification, water mask
  - ICESat-2 ATL08 canopy height parameter: h_canopy_mean_abs
  - ICESat-2 ATL08 terrain height parameter: h_te_mean

Conclusion

Dense vegetation coverage and steep slopes limit the performance of all DEMs in this study. Lidar DEMs show the best performance throughout all test sites but lack extensive coverage. COP DEM performs nearly as accurate as Lidar despite coarser resolution.

Confounding factors in S1 DEM derivation are numerous. Under ideal conditions and with accurate processing S1 products can create DEMs with good quality coming in remarkable proximity to the accuracy of DEMs with higher resolution considering the data sources. Nonetheless, single-pass interferometry DEMs (COP DEM) provide higher reliability and quality.

ICESat-2 elevation segments can serve as highly accurate reference data when proper filtering is applied and sufficient coverage is maintained.

Future work will include the optimization of S1 processing such as testing of different phase unwrapping methods as well as a closer look on the influence of specific land cover classes and vegetation height on DEM performance.

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