A new DEM of Svalbard for improved orthorecfification of Sentinel-2

Dieuwertje Wesselink, Geir Moholdt, Harald Faste Aas, Glennda Villaflor, Alexandra Messerli

Norwegian Polar Institute

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Introduction

Sentinel-2 is a new optical imaging satellite from the Europena Space Agency (ESA) that acquires medium resolution multispectral imagery over most of Earth's surface at a revisit time of only 10 days. The short revisit time is possible due to a relatively wide pushbroom sensor with an image swath of about 290 km. This gives unique possibilities for surface-change detection at a relatively high resolution (10 m), but it also enhances image distortions at the edges of the swath due to surface topography. A high-quality digital eleevation model (DEM) is essential for being able to correct these distortions such that the images can be correctly projected onto a map. We refer to the process of correcting these distortions as orthorectification, and the corrected image in map geometry is called an orthophoto. Currently, ESA performs standard orthorefitication on all raw Sentinel-2 imagery using a global DEM (PlanetDEM 90 m), and that is basis for their Level 1C orthophoto product that is freely available.

This document describes the generation of a new DEM for Svalbard that has the purpose of improving the orthophoto products (Level 1C) of Sentinel-2 imagery. The DEM has been delivered to ESA in autumn 2016, and the first test processing results using the new DEM is expected during winter 2016. As soon as the re-processed orthophotos are validated, it is anticipated that the DEM will be applied to the standard ESA processing scheme of Sentinel-2 such that all data users can take advantage of a consistent orthophoto product of highest possible quality.

DEM datsets

The Norwegian Polar Institute (NPI) surveyed all of Svalbard with high-resolution stereo-imagery during the summer months of 2008-2012. These images are now in photogrammetric production to make new topographic maps for the entire archipelago (see http://geodata.npolar.no). About half of Svalbard is currently completed, and the rest will be produced over the next few years. In areas that are not yet covered, available DEMs are either from topographic maps from 1960-1990 or various satellite-based DEMs from stereoscopy or SAR interferometry. The global PlanetDEM that ESA is currently using in the Seninel-2 processing is likely based on gridded interpolation of the contourlines in these older maps. Hence, glacier changes over the last few decades, which can be at the level of tens of meters, are not captured within this DEM.

DEMs from stereoscopic satellites like ASTER and SPOT can be of sufficient quality in many areas, but often suffer from clouds and mismatches over larger ice caps like present on Nordaustlandet, the northeastern major island on Svalbard. This is also a region where the making of new maps at NPI is on hold until a survey of ground control points has been carried out. In order to obtain a good DEM over Nordaustlandet within the timeframe of Sentinel-2 (from 2016 onwards), we decided to pre-process the 2010-2011 image catalog over Nordaustlandet without any surveyed ground control points available. Instead, we used coincident satellite radar altimetry from CryoSat-2 as a vertical reference to adjust the elevations of processed image stripes to a consistent level. This new Nordaustlandet DEM could then be mosaiced with the completed NPI DEMs at Spitsbergen and selected satellite DEMs in remaining areas to obtain a up-to-date complete DEM for all of Svalbard.

The data sources for the mosaiced Svalbard DEM are (Fig. 1):

- New DEM of Nordaustlandet (10 m resolution, 2010-2011)
- SO_NP – new completed NPI DEMs as of autumn 2016 (5 m resolution, 2008-2012)
- SPOT – freely available DEM's from the IPY-SPIRI project (40 resolution, 2007-2008)
- ASTER – filtered version (Nuth et al. 2013) of ASTER GDEM (60 m resolution, 2000-2011)
- ICESat and CryoSat-2; used for DEM coregistration and elevation bias adjustments
- New coastline based on Landsat-8 imagery from 2015 used to crop the DEM

Figure 1: *The new DEM of Svalbard (0-1800 m a.s.l.) with data sources delineated in yellow.*

Processing of Nordaustlandet DEM

The new Nordaustlandet DEM was compiled in a stepwise manner:

Step 1: Photogrammetric processing of overlapping images using semi-automated triangulation techniques within the SOCET SET photogrammetry software. The processing was done independently for 7.5 km wide image stripes that overlap by about 20%. This resulted in a total of about 60 DEM stripes that were internally consistent, but with occasional biases of a few meters between adjacent stripes. The raw DEM stripes were processed at a resolution of 5 m in WGS84 UTM zone 35.

Step 2: The DEM stripes were compared to CryoSat-2 Level 2 data from 2011 by bilinear interpolation at each altimetry point-of-closest-approach. If sufficient altimetry data were available, only points over glaciated surfaces were considered as these are most accurate. For the smaller stripes in the north which mostly cover land, all data points were taken into account. Figure 1 shows all these comparison points and their elevation difference. Some DEM stripes, especially in the middle of Austfonna, had elevation biases of up to 5 m. To make the DEM stripes as consistent and accurate as possible, we adjusted each DEM stripe according to the median bias with respect to the altimetry.

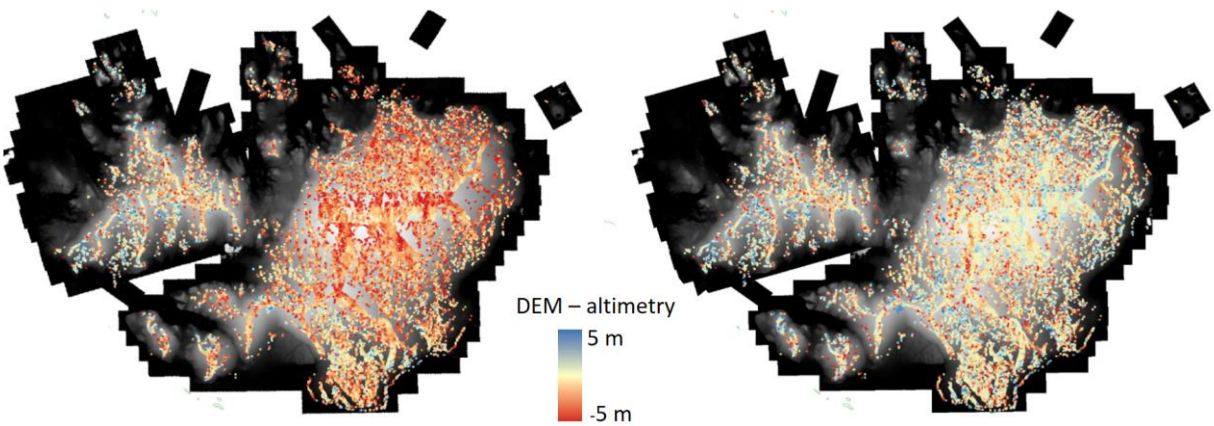

Figure 2: *Elevation difference between the Nordaustlandet DEM and CryoSat-2 altimetry before (left) and after (right) bias adjustment over glaciated surfaces.*

Step 3: We bilinearly resampled the DEM stripes to 10 m and mosaicked them together by a blending function over their overlapping areas. As the overlapping areas are around 1.5 km wide, we chose a blending distance of 1 km. This mosaiced DEM was then cropped with a Svalbard coastline that had been previously updated along all marine glacier fronts using Landsat-8 imagery from 2015.

Step 4: Due to some smaller clouds and occasional image mismatches, the DEM contained several blunders in the form of holes, spikes and high noise. These areas were identified from hillshade and slope visualizations and masked out. The diameter of the holes/spikes were 100-500 m and the larger blunders up to a few kilometers. We filled these holes using the "Close gaps" function within the SAGA module of the QGIS software. Figures 3-4 show sub-images of the DEM before and after blunder correction. The end result is a smooth DEM in 10 m resolution without any major blunders.

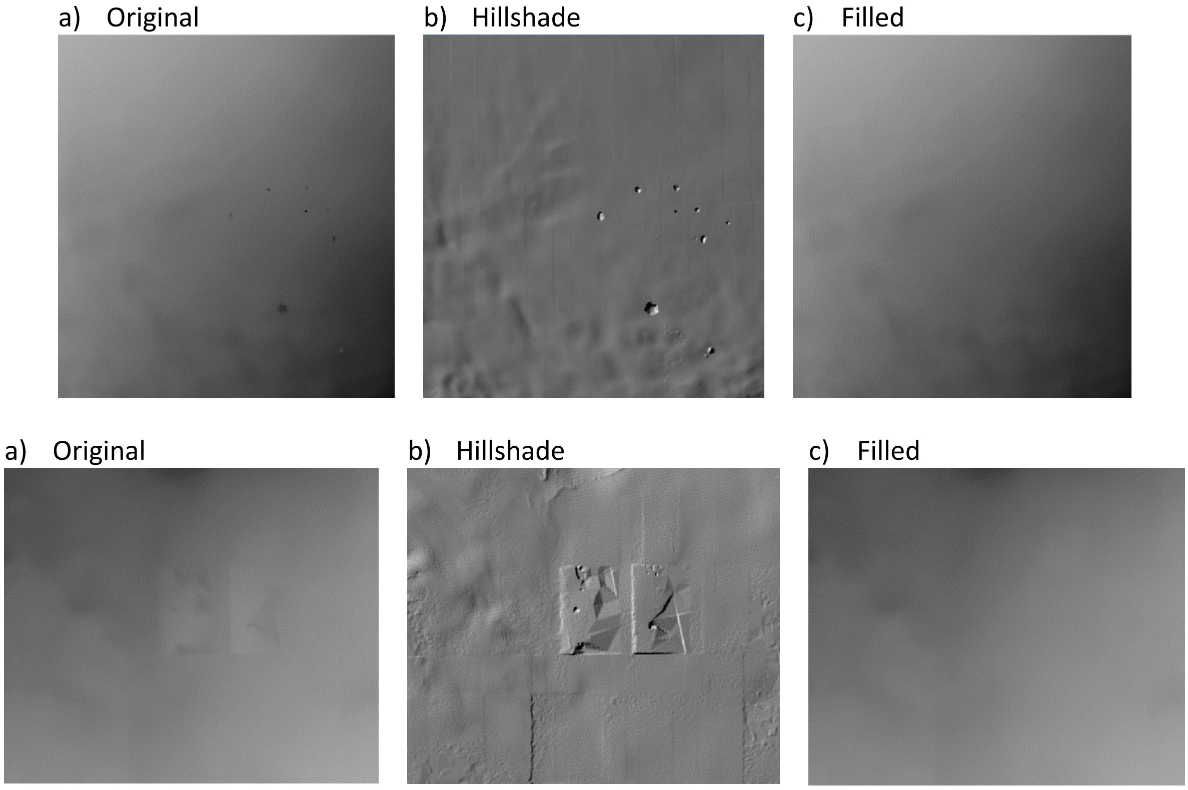

Figure 1: *Sub-images from the DEM showing two examplea of blunders; a) the original DEM, b) the hillshade, and c) the final DEM were blunders have been masked out and filled by interpolation.*

Mosaicing of Svalbard DEM

Before combining the DEMs, we compared them with ICESat laser altimetry (2003-2009) to check for georeferencing errors and potential elevation biases. We did this over over non-glaciated surfaces to avoid impacts from glacier changes, and we used ICESat rather than CryoSat-2 due to it's smaller ground footprint (70 m) which gives a better accuracy in steep terrain. Based on this comparison, the SPOT DEMs [*Korona et al.*, 2009] were individually co-registered to ICESat [*Nuth and Kääb*, 2011] to correct for errors in the range of a few tens of meters horizontally and a few meters vertically. The filtered version of ASTER GDEM that we used had previously been co-registered and smoothed with a low-pass filter in the frequency domain to remove artifacts due to DEM stacking [*Fujisada et al.*, 2005; *Nuth et al.*, 2013]. The SO_NP DEMs and the Nordaustlandet DEM were not adjusted.

The quality-controlled DEMs were then resampled with bilinear interpolation to a common refrence grid at 20 m resolution, consistent with the SO_NP DEM in WGS84 UTM zone 33. Next, these DEMs were mosaiced together in the order and priority of (1) SO_NP, (2) Nordaustlandet DEM, (3) SPOT, and (4) ASTER GDEM. This means that the aerial photogrammetry DEMs were used in all areas where available, while the SPOT DEMs and ASTER GDEM were used to fill in remaining holes (Fig. 1). Finally, we cropped the DEM with the updated Svalbard coastline from 2015 to avoid erroneous elevations in the ocean and where marine glaciers have retreated considerably over the last years. As a last quality control, we validated the DEM with ICESat and CryoSat-2 altimetry from the last decade (Fig. 4). The comparison shows no apparent biases, and the DEM precision is well within 10 m for ICESat.

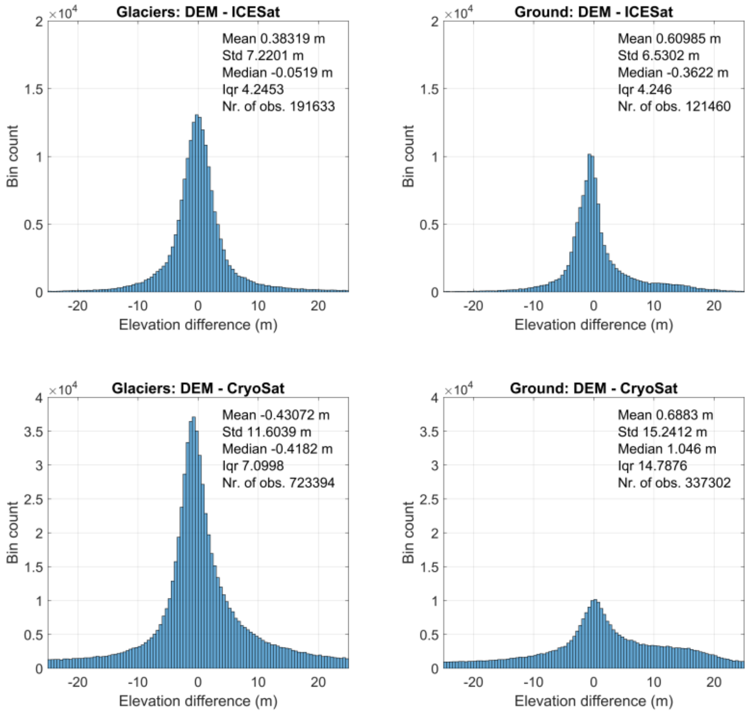

Figure 4: *Histograms with elevation differences between the Svalbard DEM and altimetry from ICESat (2003-2009) and CryoSat-2 (2011-2016) over glacier cover and ground cover.*

Comparison with PlanetDEM

The data sources and uncertainties of the global PlanetDEM is only partly documented. To assess the quality of PlanetDEM on Svalbard, we resampled it to the same grid as the new Svalbard DEM and then differenced the two grids. The results (Fig. 5) show considerable errors in Planet DEM, largely reflecting glacier changes over the last decades. This is most pronounced over the frontal areas of marine glaciers which are generally in a phase of thinning and retreat, especially in southwestern Svalbard. The apparent coastline in PlanetDEM often extends several kilometers beyond the current one, and elevations errors in these areas can be more than 100 m. An opposite bias can be seen in the interior of Austfonna related to ice cap thickening [*Moholdt et al.*, 2010].

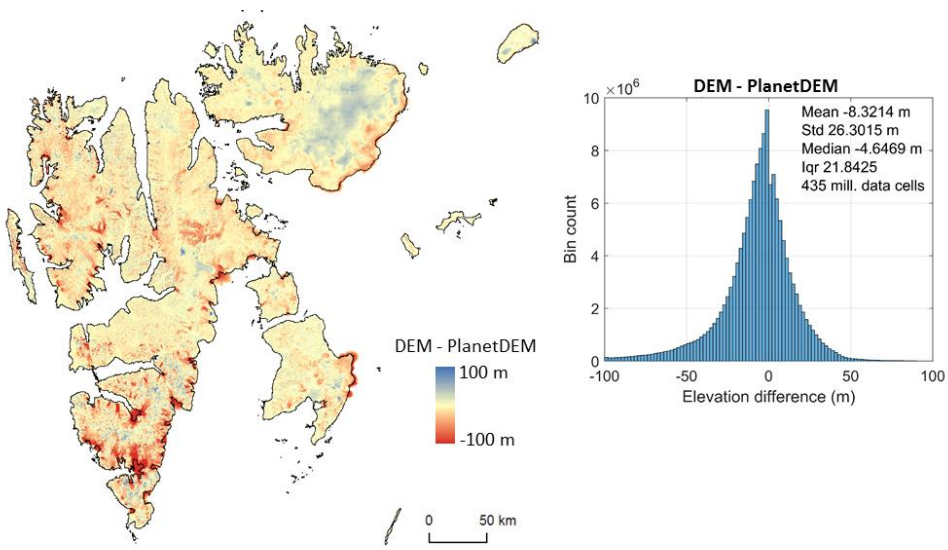

Figure 5: *Elevation comparison between the new Svalbard DEM and the global PlanetDEM. The current coastline digitized from Landsat-8 imagery in 2015 is shown in black.*

Impacts on orthorectification

Geolocation errors resulting from the orthorectification process are a function of the local DEM error and the across-track distance from nadir in the pushbroom swath. In case of the 290 km image swath of Sentinel-2, the orthophoto distortion error will range from 0% at the center to 18% at the edges of the swath. Potential errors in satellite orbits and camera orientation (not considered here) will further enhance the geolocation errors, but in a more systematic pattern that is easier to correct in post-processing. Considering the PlanetDEM errors (Fig. 5), the current Sentinel-2 orthophotos are expected to be most distorted in the coastal regions were glacier retreat and thinning have been substantial. At the edges of an image swath, the orthophoto error can be up to a few tens of meters (i.e. a few pixels) which can further double with respect to the same location in another image at the opposite side of a swath. This theoretical consideration is confirmed by a practical example applying image cross-correlation on a set of Sentinel-2 scenes over marine glaciers in the Kongsfjorden region (Fig. 6). The apparent displacement pattern between two scecens from consequtive days (Fig. 6c) reflects the expected error from PlanetDEM oerthorectification (Fig. 6b) rather than the actual glacier displacement which is almost negligible at the time scale of one day (Fig. 6d). Note that the largest orthophoto errors occur in the sea where glaciers have retreated (red zone in Fig. 6b) although this is difficult to show in practice since images decorrelate over water.

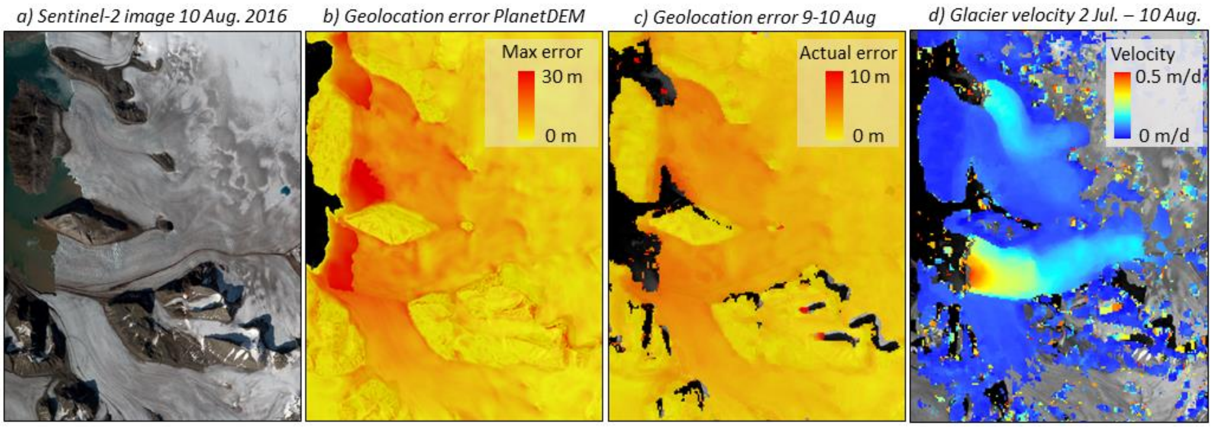

Figure 6: *Analysis of impacts of DEM erros on the orthorectification of (a) Sentinel-2 image over Kongsfjorden, showing (b) theoretical geolocation error for the edge of an image swath considering known PlanetDEM errors, (c) actual geolocation error based on cross-correlation of two images taken a day appart when (d) glacier displacement is expected to be more localized and smaller than 1 m.*

Conclusions

We have compiled a new DEM over Svalbard for use in ESA's orthorectification of Sentinel-2 imagery. All source data of the DEM dates from the last decade which minimizes the impact of glacier change, a major error source in the current PlanetDEM that is used in ESA's processing. We have shown that existing Level 1C images can contain orthorectification errors of several pixels (tens of meters) in areas of substantial glacier thinning and retreat. These distortions can vary from scene to scene due to different image acquisition geometries, and that makes it difficult to do accurate time series analyses of Sentinel-2 imagery on Svalbard. To minimize this problem for all image users, we recommend that ESA implements an up-to-date DEM in their standard L1C processing. This will improve the orthorectification accuracy to a sub-metre level in most areas and to a metre-level in areas with rapid glacier changes, both sufficient for most applications of Sentinel-2.

References

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