Advances in automatic InSAR-derived TanDEM-X DEM editing

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Abstract

InSAR-derived digital elevation models (DEMs) are currently the best way to generate global and homogeneous products representing the Earth's topography. Nevertheless DEMs derived from InSAR are not always complete and can contain artifacts (e.g. invalid values caused by the side-looking nature of SAR) or not represent the surface height in case of penetration into volumetric targets such as forests or snow covered regions. For these reasons the global TanDEM-X DEM has been completely edited at 30m resolution, in order to make it suitable for a large number of applications, such as orthorectification, processing of SAR acquisitions and hydrological modelling. Indeed, the results of this gap-less global TanDEM-X DEM version are currently being used for the processing of the new TanDEM-X data to generate an updated layer, the so-called TanDEM-X DEM 2020. Moreover, TerraSAR-X and TanDEM-X are continuing the bistatic operation and new interferometric acquisitions allow for the generation of further DEM updates, for example for monitoring dynamic changes in the cryosphere or in forested areas. Each new DEM can have gaps or noisy water surfaces, which need to be edited as well. For these newly generated DEMs we developed an advanced automatic editing as direct extension of the interferometric processing chain. The process includes the generation of different land cover maps and maps of parameters describing the acquisition geometry to facilitate the editing of the DEM in the best possible way. This paper presents the new editing approach.

1 Introduction

Digital Elevation Models (DEMs) are of fundamental importance for a large variety of scientific and commercial applications. Precise and up-to-date information about the Earth's topography is required in many geoscience areas, such as geology, forestry, glaciology, oceanography, and hydrology. As an example, the availability of a reliable DEM represents a precious input for the assessment of hydrogeological risk or the estimation of damages in case of natural hazards, such as flooding.

The global TanDEM-X DEM has been generated from bistatic X-band radar data, acquired between 2010 and 2015 by the two German twin SAR satellites TerraSAR-X and TanDEM-X [1]. It is currently the global single-sensor DEM product with the completest data coverage, including 99.89% of all the landmasses [2].

Such a DEM is the pure result of the interferometric processing and subsequent mosaicking of overlapping acquisitions. It has an independent ground resolution of 12 m and has been released in three different postings of 0.4, 1, and 3 arcsec, approximately corresponding to 12, 30, and 90 m, respectively. Moreover, it is specified with an unprecedented relative height accuracy for a global DEM product, which is under 2 m over flat areas at a 90% confidence level. Remarkably, the actual performance is far better than the specification, showing that 50% of the delivered geocells (extending by $1^\circ \times 1^\circ$ latitude/longitude) are characterized by a relative height accuracy under 1 m [2, 3].

This global DEM has been then edited by applying the editing algorithm described in [4]. The fully automatic editing of the TanDEM-X DEM has been performed at 30 m resolution in order to limit the computational load.

We now concentrate on the up-to-date DEM generation and editing from single high-resolution scenes. To do so, we consider the raw data and process it with the experimental TanDEM-X Interferometric processor (TAXI) [5]. Once this DEM is available, a complete set of maps and masks is generated on the fly as bypass product to allow for proper editing.

This paper reports the new approach designed to edit newly generated DEMs from single scenes, derived from either single- or repeat-pass acquisitions.

2 Single Scene DEM editing

The fully automatic algorithm used to edit the global TanDEM-X DEM in 1 arcsecond has been extensively described in [4]. Here we propose advances on the algorithm for editing single acquisition time-tagged DEMs at full resolution . We need to take care, on the one hand, of a series of constraints due to the single scene editing as well as of the better resolution and, on the other hand, of the direct estimation of the needed auxiliary files information, which has to be dynamically estimated. For difficult terrain, characterized by the presence of high-relief topography, the presence of voids and distorted pixels can be mitigated by mosaicking some few acquisitions with different looking geometries, acquired within a short period of time. If this is not possible, an editing procedure has to be applied. Figure 1 shows a simplified diagram of the approach developed to edit single-scene InSAR DEMs. Each of the blocks is discussed in a separate sub-chapter. Eventually, for some very difficult terrain is still necessary to acquire the area twice or three times to enable mosaics of the edited calibrated DEMs. Such mosaics can be generated through a weighted average processing, where the weights are inversely proportional to the standard deviation of the relative height accuracy. The auxiliary files can in this case also profit from the mosaic as well as the geometric masks and land cover.

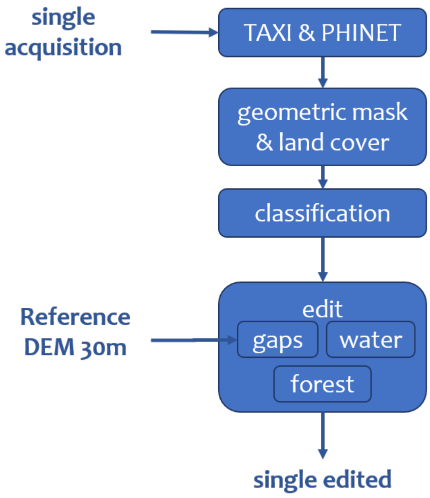


Figure 1 Diagram single InSAR DEM editing

2.1 TAXI Processor and Phi-net

The experimental TanDEM-X Interferometric processor (TAXI) [5] is used to process the single-scence aquisitions. TAXI automatically generates the DEM, the coherence as well as the estimation of the height accuracy among others. In order to be able to work at a finer resolution of only 6m, we included Phi-net [6] for the estimation of the interferometric phase and coherence. Phi-net is a novel deep-learning convolutional neural network architecture and currently represents a state-of-the-art denoising architecture in the literature for InSAR applications. An example of the performance improvement which can be reached with such an architecture is shown in Figure 2, where a TanDEM-X interferogram filtered with Phi-Net is compared to the one generated using a standard boxcar at 6m resolution.

2.2 Geometric Masks and Land Cover

The auxiliary information needed for editing a TanDEM-X DEM is in this case generated dynamically as an extension of the interferometric processing chain. A series of masks are generated, ranging from geometric distortions to land cover classification.

2.2.1 Shadow, Layover, and incidence angle

As we consider single DEMs we have to estimate a precise shadow and layover mask in order to understand which areas are not seen or are heavily distorted. For this purpose, the first step contemplates the use of a reference DEM in sufficient resolution. As the resolution of the available DEMs is often not as good as the new processed ones we need to consider an adequate resampling method, at least

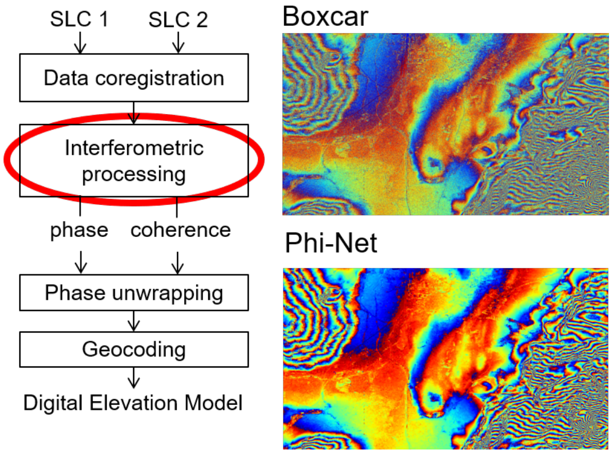


Figure 2 Estimation of the interferometric phase at full resolution (6m) using a boxcar filter (top) and Phi-Net (bottom).

cubic-spline interpolation. Then, we transform the reference DEM into slant-range geometry by back-geocoding. For each orbit position we compute the shadow, layover and incidence angle by applying the algorithm described in [7]. Finally we geocode this maps on the original grid again.

2.2.2 Water Detection

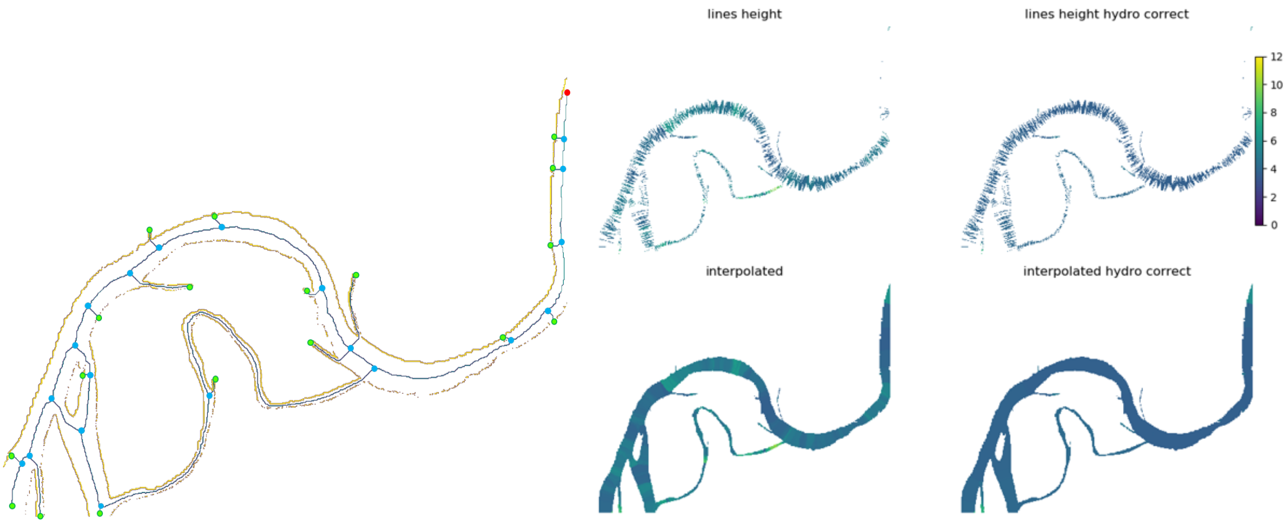
Water detection is a key part for editing a DEM that is derived from InSAR, as the phases of pixels associated to water correspond mainly to pure noise and thus its height is not reliable, even in the case of relative good coherence. The algorithm applied here is the adaption of the one used for the global water body layer (WBL) described in [8]. Water bodies are detected using markers on the coherence, followed by the application of a scharr edges filter on the coherence and a watershed algorithm to fill the water basins and land areas. The detection of water bodies is performed in areas with regular to flat slopes. As the resolution of this single scene acquisitions is much better than the resolution of the coherence maps used for generating the WBL global product and the use of the Phi-net has an extensive impact, we adapted the thresholds for selecting the initial markers to the new statistical properties of the high-resolution data.

2.2.3 Forest Detection

A forest mask, derived from a dedicated classifier, is integrated in this step. The description and implementation is the same used for the global TanDEM-X forest map which is reported in [9]. In the future, it is planned to detect also water within a deep learning-based classification framework as introduced in [10].

2.3 Absolute DEM Calibration

The single-acquisition DEMs are absolutely calibrated with respect to the global edited TanDEM-X DEM at 30m resolution. We select calibration points where no geometric issues are present and the coherence is in the fist 0.1th



(**a**) algorithm characteristics (**b**) Comparison example with and without hydrologic correction

Figure 3 Hydrologic correction of a river. (a) The yellow lines represent the 2 row shoreline, while the blue ones build the skeleton of the river. The dots in green are the starting points to navigate and correct the height level. The blue dots are confluence points that are navigated in a second step, while the red point is the last point to be navigated. (b) The top plots represent the line by line estimation of the river height, where the right side considers navigating though the river from the highest to the lowest part of the river. On the left-hand side, no navigation is performed and only the shorelines are used to estimate the height of the water.

percentile. The difference to the global DEM is used to estimate a slight plane to compensate for residual offsets and tilts. In addition to this, we define a relaxed height drift mask for detecting phase unwrapping issues, which depends on the specific height of ambiguity of the single InSAR derived DEM, by setting a dynamic threshold, which is estimated from the distribution of height difference with respect to the reference DEM.

2.4 Editing Classification

Gaps are considered as pixels that have a very low coherence. Whereas the threshold for this is normally statically set, we identify the region region by applying a watershed algorithm. Also areas that correspond to unresolved geometrical issues, such as shadow and layover or the relaxed height drift mask are gaps. Than, the water body layer (WBL) is used to separate gaps from water surfaces. Subsequently, gaps are classified depending on their location with respect to a neighbour water body, as well as the size and dispersion of the gap, as already presented in [4]. Regarding water bodies, a different editing procedure has to be applied depending on their specific classification as rivers, lakes and seas. We assume, for this publication, the classification in the global DEM to be adequate and we use it for tagging the actual estimated water bodies as either seas, lakes, or rivers, whereas the non existing water bodies in the global editing are now assumed to be ponds and treated like lakes.

2.5 Editing Process

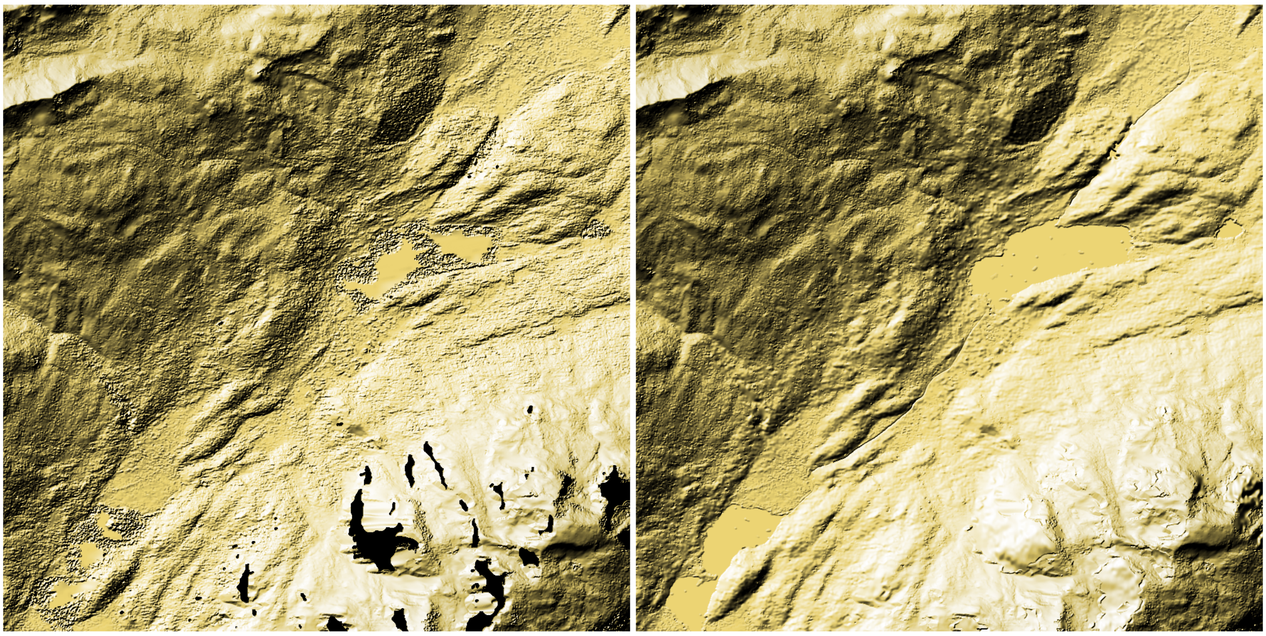
The utilized algorithms are based on the gaps filling and water-bodies editing for the global TanDEM-X DEM. Additionally we evaluate areas consider to be forested to be slightly smoothed with a gaussian filter, whose width is determined by the standard deviation of the DEM in the proximity of the considered pixel. In this way we assume to be estimating the height based on the mean penetration in the forest and we avoid considering the penetration on single independent trees.

2.5.1 Gaps Filling

The same approach described in [4] is used as standard algorithm in this case, with no further adaptation. The so called stable delta interpolation approach is applied. Here the most important part is still the estimation of the the height drift mask which is calculated in the case of single acquisitions based on the standard deviation of the height accuracy and the height difference to the reference DEM, which is in this particular case the edited global TanDEM-X DEM at 30m resolution.

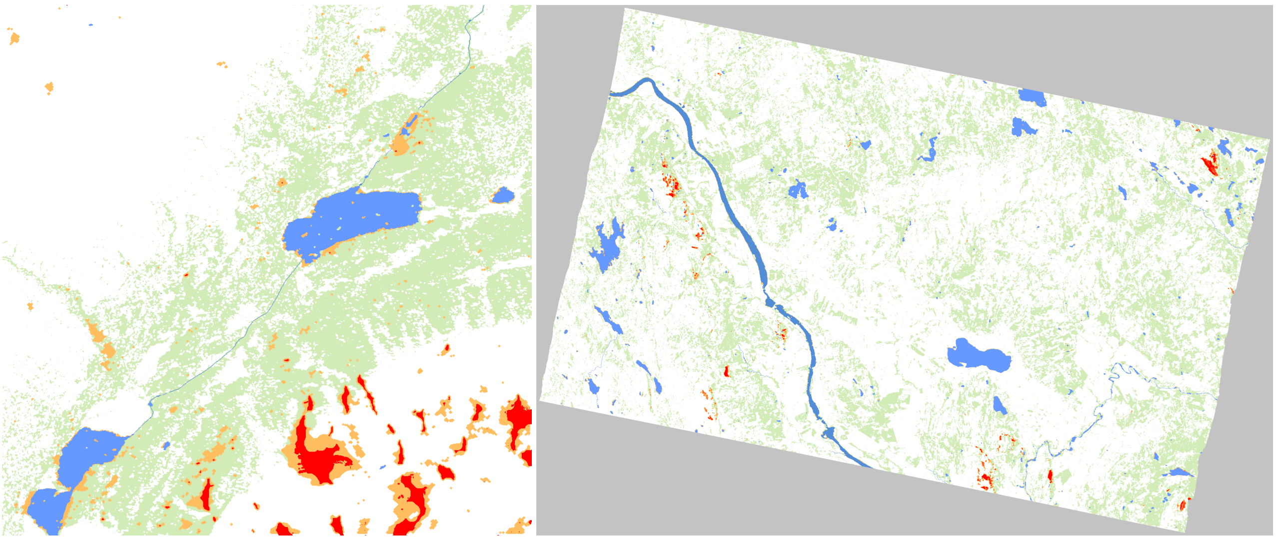
2.5.2 Water Editing

The strategy for editing single scene water bodies, such as ocean and lakes, was introduced in [4]. Here we present a simple concept for hydrologic correction of the rivers heights. In the case of global DEM the approach for flattening rivers was done in pixel-wise height estimation. In the present work, we also improve the computational performance of the flattening algorithm by considering the skeleton of a river as starting point for the flattening procedure. In figure 3 (a) we can observe the skeleton of the different river branches as the blue line and also the two row shoreline in yellow. The dots represent, depending on their color, the starting points (in green), the confluence points (in blue) or the end point (in red). For each point of the



(**a**) unedited DEM (**b**) edited DEM

Figure 4 Hill-shade images with the detail of the unedited (a) and edited (b) TanDEM-X DEM at 6m resolution for the Engadin Valley in Switzerland, centered around St. Moritz.



(**a**) example 6m Switzerland (**b**) example 12m Norway

Figure 5 Editing mask. Geometric distortions as shadow and layover are shown in red as well as height drift mask in orange. Lakes are displayed in light blue as well as a river in darker blue. The forested areas are marked in light green. The grey areas are outside of the acquired scene.

skeleton a height is determined, by assuming it to be equal to the first 10th percentile of the height of the 20 closest shoreline pixels on each side of the river. Than the algorithm *navigates* through each branch starting from the green points and it sets the water level to be equal or below the previous one. The navigation follows the skeleton until a confluence point is reached. From this confluence points the algorithm can continue only when all steams are concluded except from one. In the case of meandering, the farthest confluence point to the end point is the one selected to continue the navigation. Once the height is set for each skeleton point the non-estimated river heights are interpolated with a nearest neighbour interpolation and one meter is arbitrarily subtracted, in order to reduce the possibility to have water height values higher than the surrounding shoreline pixels. Finally, a Gaussian filter with a minimal impact is included to smooth the simple interpolation. An example of the comparison by considering the heights out of the skeleton without an hydrological correction and the calculation considering a navigation direction are shown in figure 3 (a). Here, we can appreciate the improvement obtained by following the river downstream.

3 Examples

For this section we have selected two examples showing one detail in 6m sampling and one complete scene with 12m sampling. Figure 4 shows a zoom-in the TanDEM-X DEMs before and after editing, which allows to highlight the details of the landscape. The time-tagged DEM corresponds to a single-scene acquisition and is located in Switzerland. The shown area is centered around St. Moritz and is depicted as a hill-shade image. The shown area comprises about of 36 km^2. It is possible to appreciate the benefits of the edition: water surfaces are correctly flattened, gaps are filled and vegetated areas appear smoother. In figure 5(a) the corresponding editing mask is presented. In figure 5 the areas in red and orange have been edited as gaps. Red areas correspond in this case to shadow and layover geometric distortions. In some cases areas affected by phase unwrapping errors are also set as gaps. The areas in orange correspond to the height drift mask. The water bodies are depicted in blue and edited depending on their type. Two lakes are visible as well as a river connecting them, together with some ponds. The river shown here is the Inn River, which starts further to the west. The forested areas have also been identified and are marked in light green. The second example is a complete DEM acquisition, whose hill-shade representation is shown in figure 6. This extensive example comprises an area of about $700km^2$ which presents a rather simpler topography. It is located in the east of Norway, near to the Swedish border. The range of heights extends by about 400m. It includes a wide river as well as some lakes and ponds. The edited forest is also visible in this example. The estimated height on the main wide river drop of about 20m along the entire scene, from the western part to the southern one. Figure 5 (b) shows the corresponding edited version, while the editing mask is depicted in figure 5(b).

4 Conclusions and Outlook

In this paper, we described the implemented algorithm for the "on-the-fly" edition of time-tagged, high-resolution DEMs, generated from single acquisitions. All necessary steps and intermediate masks have been briefly discussed as well as the considerations to enable the high resolution processing. The algorithms which estimates the river heights applies hydrological corrections and is highly efficient. The capabilities of the proposed approach are confirmed by the visual inspection of the two considered examples. New possibilities for the edition of DEMs generated from InSAR are being open with the estimation of forest height [11]. In this way, it should be possible to separate a digital surface model (DSM) and digital terrain model (DTM). The concepts in [10] will also be integrated in the editing chain once this is available for the all different types of forest.

5 Literature

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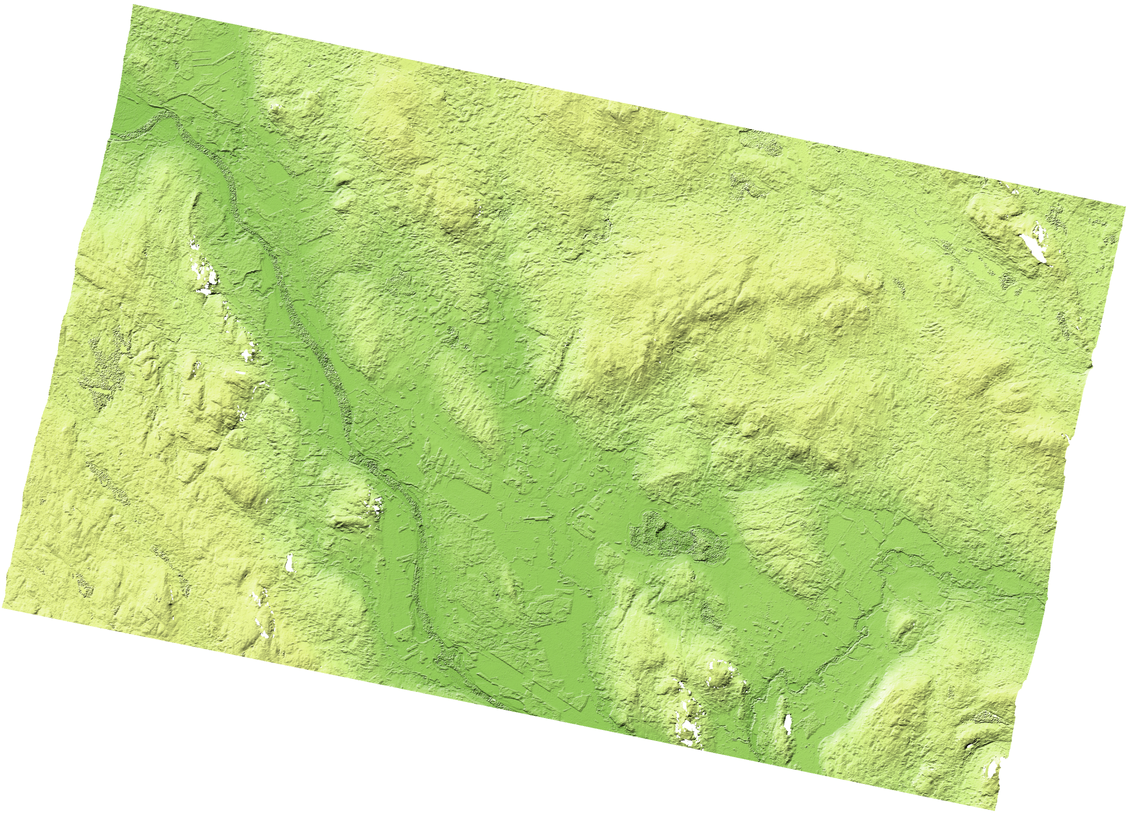
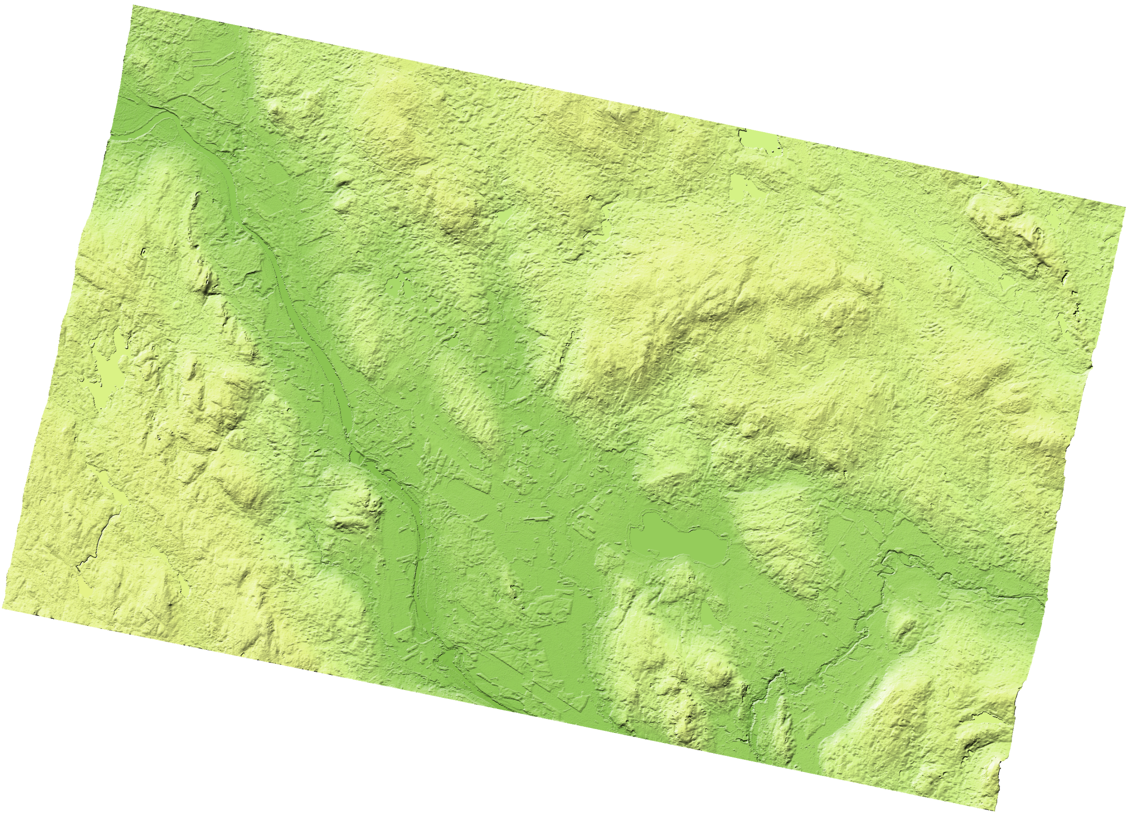


(**a**) unedited DEM



(**b**) edited DEM

Figure 6 Acquisition in Norway. The time-tagged DEM corresponds to a single scene acquisition, depicted as hill-shade images that give easy away steps and artifacts. The shown area comprises about of 700 km2 and has a resolution of 12 meters.