Need for Mutual DEM Calibration for Monitoring of Height Changes from TanDEM-X DEM Difference

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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. Monitoring topographic changes is one of the main topics, which can be assessed by evaluating the difference between two DEMs acquired at different times. However, this is only possible when the DEMs are properly calibrated, as DEMs can be affected by residual offsets and tilts. This calibration is often performed by utilizing reference tie-points, whose location and height is known a priori or well estimated through other reference sensors such as GPS or Lidar data. This is in general a manual procedure and relies on the availability of time-consistent external reference points. By exploiting persistent scatterers candidates from Sentinel-1 time-series we demonstrate the possibility to perform an automatic selection of reliable tie-points and discuss their applicability to use them to calibrate a pair of single pass TanDEM-X DEMs. In this paper we want to introduce and elaborate on the novel proposed technique and discuss its potential for the monitoring of height changes that can be in the order of magnitude of the residual calibration errors, finding possible applications for the monitoring of evolving processes, such as open-pit mining, permafrost unfreezing processes or volcanic lava flows.

1 Introduction

A precise knowledge on the Earth's topography is required by a large variety of scientific applications in geo-science areas, such as geology, forestry, glaciology and hydrology. One of the topics focuses on the monitoring of deformations or changes that correspond to different natural or artificial processes. Monitoring changes in the order of few centimeters with a precision of millimeters has been widely addressed by the InSAR community with persistent scatterers interferometry (PSI) [1], overcoming the temporal and the geometrical decorrelation to estimate deformations, deformation trends and residual terrain errors [7]. Larger height changes can be evaluated by differentiating two subsequent digital elevation models (DEM) derived from bistatic InSAR data, such as the ones acquired by the TanDEM-X mission [2]. Often, it is difficult to prove that small changes in the measured height DEM difference, in the order of only few meters, correspond to real changes, since the root mean square error (RSME) of the accuracy itself of single TanDEM-X DEMs reported on the literature is around 2 m. The accuracy can be splitted into two components the absolute accuracy and the relative accuracy [3]. The absolute uncertainty is related to the limited knowledge of the perpendicular baseline between the TerraSAR-X and the TanDEM-X satellites, whose accuracy is about 1 mm after the precise baseline calibration. This results in the presence of tilts and offsets in the single DEMs up to few meters [6]. For this reason the global TanDEM-X DEM has been consistently calibrated using external IceSAT measurements, before performing the mosaicking process. The second source of uncertainty is intrinsic to the InSAR technique. It is caused by the drop of coherence and its impact changes with respect to the bistatic acquisition geometry impacting the phase unwrapping process. The relative accuracy, also called point-to-point accuracy can be very well estimated and it is mainly dependent on the height of ambiguity and the land cover type [4]. The relative accuracy can be considerably improved by applying a certain multi-looking withing the InSAR processing for the estimation of the interferometric phase. Typical accuracies by 50 m height of ambiguity and a pixel spacing of 20 m is in the order of 0.4 m. In order to detect and quantify changes from DEM differences, we need therefore to compensate for possible residual offsets and tilts and reduce the relative height error as much as possible.

This paper proposes a method to perform a precise mutual calibration of two time-tagged DEMs before performing DEM differencing, in order to be able to correctly detect changes which are in the same order of magnitude of the baseline calibration accuracy. The advantage of this approach is that it does not require for the availability of external reference data to be manually set, such as GPS data, but simply relies on the use of reliable natural targets, which can be used as tie-point for performing the mutual calibration.

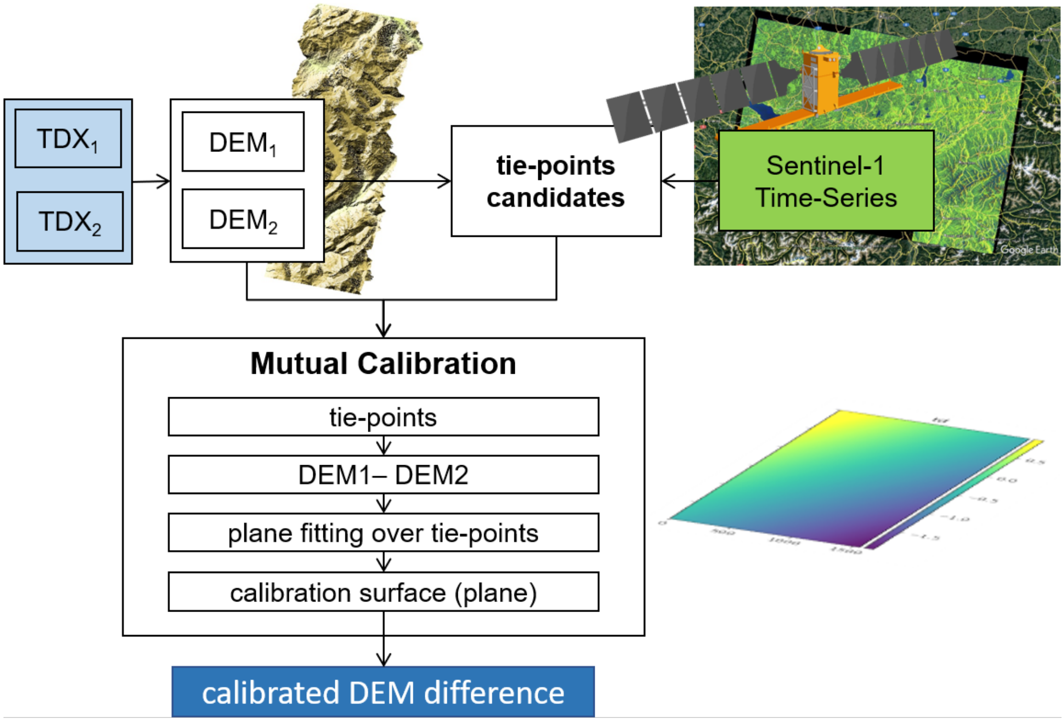

Figure 1 Overview of the proposed method for the mutual calibration of two TanDEM-X single-scene DEMs, by utilizing natural tie-points targets selected from Sentinel-1 repeat-pass time-series.

2 DEM Mutual Calibration

The mutual calibration of time-tagged InSAR DEMs requires a priori knowledge on stable areas, i.e. those that have not experienced height changes. The success of the calibration relies on the availability of external reference, such as GPS points. When considering DEM differencing, an absolute calibration of the single DEMs is not needed, but rather both DEM have to be correctly refferenced to each other in what is called mutual calibration. The idea is to identify natural targets that are stable enough to be used as tie-points for correctly anchoring the two DEMs. For this purpose, we evaluate the use of Sentinel-1 persistent scatterer (PS) candidates [1, 7], thanks to the regular availability of Sentinel-1 time-series at global scale.

Figure 1 shows the overview of the proposed mutual calibration process. We consider a pair of single-scene TanDEM-X DEMs as input, and a Sentinel-1 time-series possibly acquired during the same period. The tie-points candidates are derived from the Sentinel-1 time-series by applying a series of selection criteria, as described in the following, which can assure the good quality of the selected tie-points for the considered purpose. Afterwards, such tie-points are used compensate for potential residual tilts and offsets between the two TanDEM-X DEMs. To do so, the DEM difference over the tie-points is considered to fit a calibration surface, e.g. a plane. The actual DEM difference is then calibrated with the plane surface. In this way we compensate for the residual offsets and tilts.

Figure 2 shows the single steps required to properly select the calibration tie-points. On the left-hand side, as a first step we consider the Sentinel-1 repeat-pass time-series. Geometric distortions such as shadow and layover are discarded as tie-points candidates. Then, we also exclude snow and ice-covered regions from an external land cover map [4, 9]. Moreover, we only consider pixels characterized by the presence of low-relief local topography, by setting a threshold on the predominant local slope using the global TanDEM-X DEM as reference product. As a next step, we calculate the dispersion amplitude index, as proposed in [1]. Finally, by setting a threshold on such an index we obtain a set of tie-points candidates. The right-hand side of Figure 2 shows the adaptation of the tie-point candidates to the actual TanDEM-X InSAR pairs from which the DEMs to be calibrated were generated. Here, we also need to take care of the geometric distortions since they are different than the ones characterizing the Sentinel-1 the time series, given the different acquisition geometries of the two SAR constellations. Then we discard points whose bistatic coherence is below a pre-defined threshold and whose signal-to-noise ratio (SNR) is larger than a given value. This condition allows us to ensure a good quality of the considered targets within the DEM data. The estimation process of the used algorithm parameters is explained in the following sub-sections.

2.1 Geometric Distortions

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 an external reference DEM. As the resolution of the external DEM is often not as good as the newly processed ones we need to consider an adequate resampling and interpolation method. For this purpose, we consider cubic-

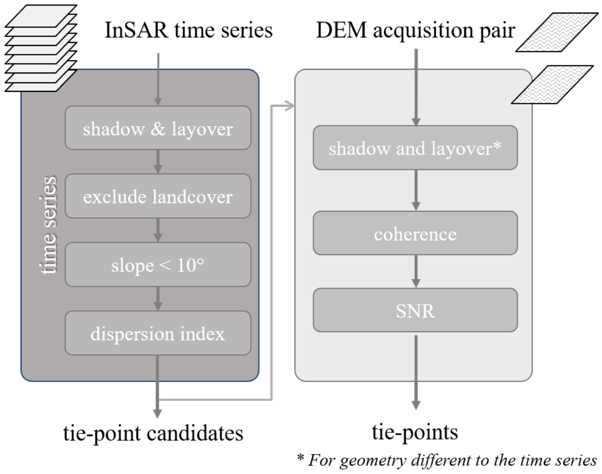

Figure 2 tie-points selection steps

spline interpolation of the external DEM with a larger pixel spacing. Then, we transform the reference DEM into slant-range SAR geometry by back-geocoding. For each orbit position we compute the shadow and layover by applying the algorithm described in [5]. Finally we geocode the obtained maps on the original grid again.

2.2 Amplitude Dispersion Index

The amplitude dispersion index is defined as [1]:

$$\mathcal{D}_A = \frac{\sigma}{\mu}, \tag{1}$$

where, for each pixel of the co-registered InSAR time-series, μ represents the temporal mean value of the amplitude and σ the corresponding standard deviation. In presence of high-values of SNR, low values of the amplitude dispersion index are also a good approximation for high temporal phase coherence [1], which is a necessary condition for assuring a good consistency of the selected points within the two InSAR DEMs as well.

2.3 Local Slope

The predominant local slope s is computed from the heights h of the neighboring pixels in each of the two coordinate directions, considering also the diagonal neighbor pixels and weighting their contributions [10] in the following way:

$$s(x, y) = arctan\left(\sqrt{\frac{dh}{dx}^2 + \frac{dh}{dy}^2}\right) \tag{2}$$

where x and y represent the horizontal and vertical coordinates, respectively.

2.4 Land Cover

The filtering of unreliable land cover types is necessary in order to avoid the selection of calibration targets, whose topographic height might be affected by the presence of snow and ice and, consequently, by radar wave penetration effects [8, 9]. These areas are therefore filtered out in the tie-points selection process and, for this purpose, external land cover information is exploited. One should note that penetration effects also occur over vegetated areas, which are anyway excluded due to the low coherence caused by a combination of both temporal and volume decorrelation. Snow-covered regions could remain more coherent even in presence of penetration, representing therefore a potential source for false alarms.

2.5 Bistatic Coherence

The bistatic coherence γ_{tot} is the key quantity for assessing the quality of the generated DEM from single-pass InSAR, since it quantifies the amount of noise in the interferogram. It is defined as the absolute value of the normalized cross-correlation coefficient between the interferometric image pair. γ_{tot} can be estimated from the following equation:

$$\gamma_{\mathrm{tot}} = \frac{|E[u_1 u_2]|}{\sqrt{E[|u_1|^2 |u_2^*|^2]}} \tag{3}$$

where u_1 and u_2 represent the master and slave images, respectively, E is the expectation value and $*$ is the complex conjugate operator. A threshold is applied on the bistatic coherence to filter out areas characterized by a poor quality in the considered DEMs and consequently by higher elevation errors.

2.6 SNR

Finally, a further threshold is applied on the SNR of both TanDEM-X bistatic acquisitions, in order to assure the selection of stable natural targets. The SNR is computed as:

$$\mathrm{SNR} = \frac{\beta^0 - \beta^n}{\beta^n}, \tag{4}$$

where β^0 identifies the temporal mean radar brightness and β^n is the noise equivalent β^0, which represents the noise equivalent beta nought, i.e. the system noise floor.

3 Example of Calibration

An example of the mutual calibration of a pair of TanDEM-X single-scene DEMs is shown in Figure 3. The DEMs were generated from TanDEM-X bi-static acquisitions over Japan in the end of summer of 2020 and begin of spring 2021. On the top left of the figure the tie-points are shown in green. The main central area characterized by a dense presence of tie-points correspond to the city of Koriyama. On the top right the fitted plane used for the calibration is depicted. One can see that offests and tilts in the order of ± 1 m are estimated. On the bottom of the figure, the DEM difference is depicted, showing, on the left-had side, the raw difference or uncalibrated one, while, on the right-hand side, the resulting calibrated DEM difference. The uncalibrated DEM difference shows positive and negative values. Looking at the calibrated DEM difference, we can see a large white area close to 0 m in correspondence of the urban area. The large blue structures correspond to

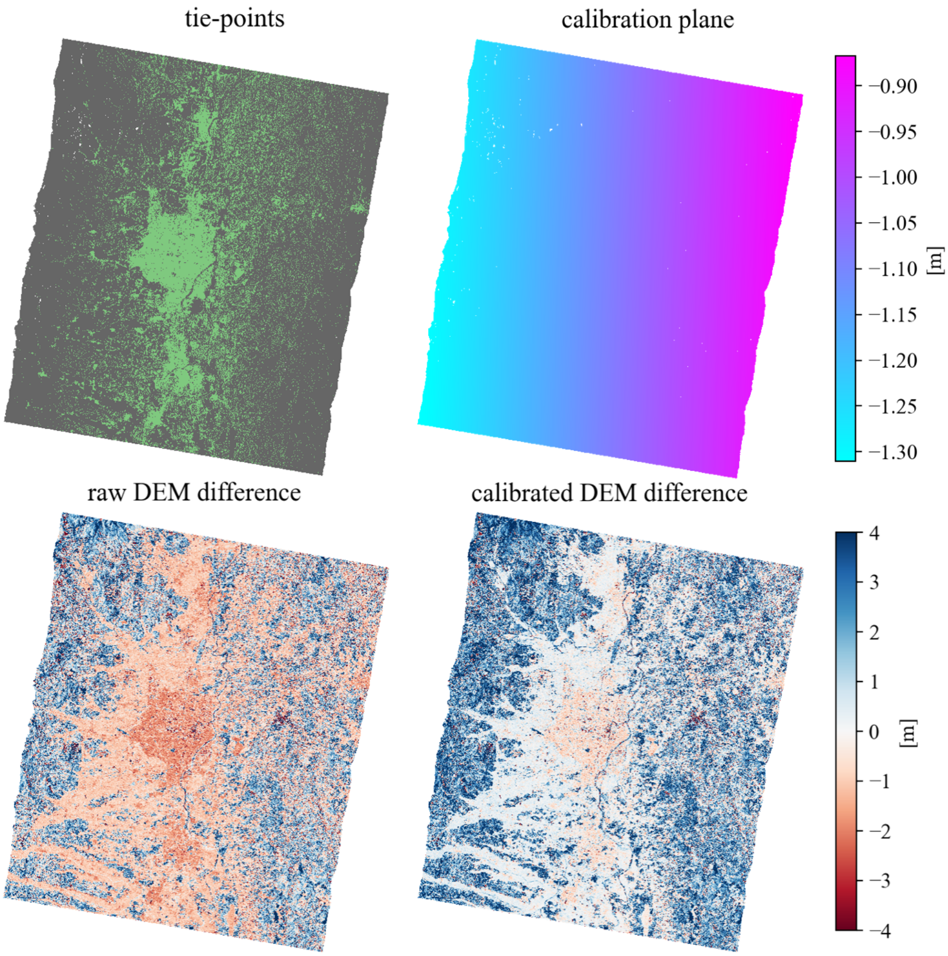

Figure 3 Example of mutual DEM calibration considering a pair of TanDEM-X DEMs acquired over the city of Kōriyama, Japan. On the top from left to right: selected calibration tie-points (green) and fitted calibration plane. On the bottom from left to right: uncalibrated DEM difference, calibrated DEM difference.

areas covered by deciduous broad leaved forests, characterised by seasonally shedding foliage and no foliage for part of year. The light blue areas correspond to agricultural fields. Figure 4 shows the histograms before and after the calibration of the DEM difference over the selected tie-points. Here we can see an increase in the peak of the distribution, which translates into a narrowing of the distribution, and the correct positioning of the histogram main lobe around 0 m. The high difference value retrieved over vegetated areas are caused by different penetrations of the radar waves in the vegetation of the two considered DEMs, and can be spotted in the right part of the histograms.

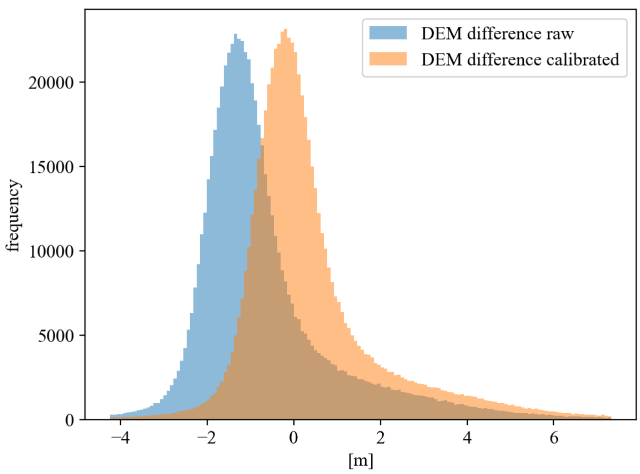

Figure 4 Histogram of the DEM difference over the tie-points, before (blue) and after (orange) applying the proposed mutual calibration algorithm.

4 Conclusions and Outlook

In this paper, we described a novel algorithm for the automatic mutual calibration of a pair of time-tagged DEMs. The technique elaborates on the selection of natural tie-points derived from the pre-selection of persistent scatterer candidates from Sentinel-1 time-series. Since Sentinel-1 coverage is global, with a revisit time of 12 days, it is possible to have a time-consistent selection of natural tie-points. Natural targets from Sentinel-1 are appropriate for mutual calibration of two single-pass TanDEM-X DEMs under certain conditions, which have been described and analyzed in detail, such as a sufficient interferometric coherence and signal-to-noise ratio to assure a high quality of the selected tie-points. This method is envisioned to be self-sufficient, without the need for external GPS or LiDAR measurements, and to be fully automatic without any manual intervention.

One should be aware, that residual offests and tilts caused by uncertainties on the estimation of the interferometric baseline are not always present in TanDEM-X data but, on the other hand, it is not possible to detect their presence with a priori information. This is the reason why a precise mutual calibration is needed before performing DEM differencing, since the tilts and offset of few meter can be often confused with the relative accuracy and yield misleading results in the downstream scientific applications. Finally, the proposed technique represents a key first step for a variety of scientific applications based on DEM differencing and will allow for significantly improving the accuracy of the derived products of elevation changes.

5 Acknowledgment

The performed activity has been partially financed through the ESA EXPRO+ AlpSnow Project (Contract No. 4000132770/20/I-NB) and it was partially performed at the University of Houston under a contract with the NASA Surface Topography and Vegetation (Grant QK-WEF8XLMTT3). The presented technique is currently patent pending under: A computer-implemented method for calibrating a pair of digital elevation maps, Deutsche Patentanmeldung Nr. 10 2023 123 310.6, Priority 2022-08-30.

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