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Accuracy assessment of the global TanDEM-X Digital Elevation Model with GPS data

Birgit Wessel *, Martin Huber, Christian Wohlfart, Ursula Marschalk, Detlev Kosmann, Achim Roth

German Remote Sensing Data Center (DFD), German Aerospace Center (DLR), Oberpfaffenhofen, 82234 Wessling, Germany

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ABSTRACT

The primary goal of the German TanDEM-X mission is the generation of a highly accurate and global Digital Elevation Model (DEM) with global accuracies of at least 10 m absolute height error (linear 90% error). The global TanDEM-X DEM acquired with single-pass SAR interferometry was finished in September 2016. This paper provides a unique accuracy assessment of the final TanDEM-X global DEM using two different GPS point reference data sets, which are distributed across all continents, to fully characterize the absolute height error. Firstly, the absolute vertical accuracy is examined by about three million globally distributed kinematic GPS (KGPS) points derived from 19 KGPS tracks covering a total length of about 66,000 km. Secondly, a comparison is performed with more than 23,000 "GPS on Bench Marks" (GPS-on-BM) points provided by the US National Geodetic Survey (NGS) scattered across 14 different land cover types of the US National Land Cover Data base (NLCD). Both GPS comparisons prove an absolute vertical mean error of TanDEM-X DEM smaller than ±0.20 m, a Root Means Square Error (RMSE) smaller than 1.4 m and an excellent absolute 90% linear height error below 2 m. The RMSE values are sensitive to land cover types. For low vegetation the RMSE is ±1.1 m, whereas it is slightly higher for developed areas (±1.4 m) and for forests (±1.8 m). This validation confirms an outstanding absolute height error at 90% confidence level of the global TanDEM-X DEM outperforming the requirement by a factor of five. Due to its extensive and globally distributed reference data sets, this study is of considerable interests for scientific and commercial applications.

1. Introduction

Since September 2016 the new TanDEM-X Digital Elevation Model (DEM) can be seen as one of the most consistent, highly accurate and completest global DEM data sets of the Earth surface. This novel product will play a major role in a wide range of various regional and global applications analyzing physical and biological processes of the Earth surface (Zink et al., 2014). The height information was derived by applying single pass Synthetic Aperture Radar (SAR) interferometry. The corresponding pairs of images were acquired by the twin satellites TerraSAR-X and TanDEM-X, which fly in a close helix formation with distances between 300 and 500 m of each other (Zink et al., 2014). Bi-static interferometry is applied by transmitting pulses from the antenna of only one of the satellites and by receiving the backscattered signals simultaneously with both. Although SAR interferometry is well suited to globally map the Earth's surface in a short period of time, due to its 'day and night' and its 'all-weather' observation capability, the measured height corresponds to the reflective surface of the X-Band signal. In general, the TanDEM-X height model can be regarded mostly as a Digital Surface Model (DSM) rather than a Digital Terrain Model (DTM). However, there exist some exceptions for areas where the SAR signal penetrates the surface by some meters – e.g. in cases of ice, snow or vegetation. Consequently, the umbrella term DEM, comprising any kinds of elevation models, is the best suited for the TanDEM-X DEM. This product is available for scientific users at the German Aerospace Center (DLR, March 2018), commercial users can get the DEM from Airbus Defense and Space as so-called WorldDEM in different versions, e.g. with geoid elevations or further value-additions (WorldDEM, March 2018). The used SAR data for the global DEM production were acquired between December 2010 and January 2015 in StripMap mode with horizontal transmit and receive polarization (Krieger et al., 2007, Wessel, 2016). All land masses are covered at least twice (Borla Tridon, et al., 2013) to facilitate dual-baseline phase unwrapping (Lachaise et al., 2018) and to reach the random height accuracies by averaging individual DEM scenes with an

* Corresponding author.
E-mail address: Birgit.Wessel@dlr.de (B. Wessel).

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interferometric SAR-specific mosaicking approach (Gonzalez and Bräutigam, 2015, Gruber et al., 2016). The generated TanDEM-X DEM has a 0.4 arc second posting and resolution with a specified 10 m absolute vertical accuracy (90% linear error, LE90) and 2 m relative accuracy resp. 4 m for areas with slopes larger than 20% (90% linear point-to-point error). The absolute height error of the final DEM was established by calibrating the individual data takes based on ground control points from ICESat (Ice, Cloud and land Elevation Satellite) GLA14 products and image control points (Gruber et al., 2012).

The next step is the validation of the specified quality of the final TanDEM-X DEM at a larger scale, which would be of considerable interests for the scientific and commercial users. Due to the limited availability of the TanDEM-X DEM so far, only a few works on regional scale report about the validation of the DEM (Baade and Schmullius, 2016; Rexer and Hirt, 2016). The internal validation effort regarding the absolute vertical accuracy of the global TanDEM-X DEM is based on ICESat data (Rizzoli et al., 2017). ICESat points are also integrated into other global DEM validation work, e.g. for AW3D (ALOS World 3D) from the optical PRISM senor onboard the ALOS satellite (Takaku et al., 2016). The study of Rizzoli et al. (2017) states that the TanDEM-X DEM reaches with 3.5 m the global absolute accuracy goal of 10 m (90% linear error, LE90) by far. In our study, the absolute height accuracy of the TanDEM-X DEM should be validated globally as well, but with independent, higher accuracy data sets that have not been used for the generation of the DEM. Global Positioning System (GPS) points, which were chosen for this task, are a common measure to assess the accuracy of global DEMs (Rodríguez et al., 2006; Jacobsen and Passini, 2010; Mouratidis et al., 2010; Gesch et al., 2012; Baade and Schmullius, 2016; Bolkas et al., 2016; Gesch et al., 2016; Rexer and Hirt, 2016). Gesch et al. (2012) and Gesch et al. (2016) use GPS data to describe the absolute height error for 14 land cover classes in the United States separately for the global Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM2). Bolkas et al. (2016) express the importance of selecting ground control points according to different terrain characteristics like slope and land cover types to get a representative Root Mean Square Error (RMSE) for the estimation of the DEM uncertainty. However, the availability of GPS points suited for world-wide validation is very limited and of high uncertainty. Therefore, one unique GPS data set used in this work was acquired in special campaigns in 2008 and 2009 for exactly this purpose (Kosmann et al., 2010).

The primary goal of the validation work performed in this paper is the characterization of the vertical accuracy of the TanDEM-X DEM by two independent, highly accurate and extensive GPS data sets. All reference data sets and the used DEM validation approach are introduced in the second chapter. Chapter three describes and discusses the results of the GPS analyses. In addition, comparisons with two high-resolution DSMs and a DTM are conducted. Chapter four completes the paper by a summary of our results.

2. Materials and methods

Absolute vertical accuracy assessment requires highly accurate and independent reference data. The accuracy of such data sets should be at least three times more accurate than the evaluated data set (Maune, 2007, p. 407). Here, we want to validate the 10 m LE90 absolute height error requirement, which results in a maximum error of 3.3 m LE90 for a reference data set. This leads to an accuracy requirement of a Standard Deviation (STD) being less than 2 m, which in turn is a very ambitious figure for a global validation data set. A potential existing data set that fulfils the demanded requirements is the ICESat GLA14 elevation product (Zwally, 2002; Carabajal and Harding, 2005). A subset of around 10% of the GLA14 data was used within the DEM generation process for the block adjustment of the individual DEM acquisitions (Wessel et al., 2008; Huber et al., 2009; Gruber et al., 2012). The remaining ICESat points built the base for a DEM accuracy analysis as described in Rizzoli et al. (2017). In this study the following independent GPS data sets were used.

2.1. Kinematic GPS tracks

An extensive ground truth data campaign was set up for the TanDEM-X mission in 2008 and 2009 to gain global reference data with an accuracy of STD <2 m (Kosmann et al., 2010). Transects on every continent (except Antarctica) were measured with the kinematic Global Positioning System (KGPS) method. The basic concept of this collection was to mount a GPS antenna on top of a car and drive along roads across the continents.

The TanDEM-X data was basically acquired in strips along the north-south direction. In order to enable the detection of systematic errors smaller than the absolute accuracy across the track direction, the GPS transects were driven mainly in east-west direction. This world-wide acquisition was realized in close cooperation with the FIG (International Federation of Surveyors). Interested scientists and organizations were invited to participate in the DEM verification efforts with KGPS tracks. The vertical error of the kinematic GPS tracks should not exceed 0.5 m. The use of precise differential GPS (PDGPS) using local reference stations is very time-consuming and cost-intensive and Continuously Operating Reference Station (CORS) networks are not available world-wide. Therefore, an extensive GPS post-processing approach called Precise Point Positioning (PPP) had been used (Ramm and Schwieger, 2007; Schweitzer et al., 2010). This approach did not require a GPS reference station network, but precise orbit and time information. Additionally, satellite antenna offsets and variations as well as phase wind up corrections had to be considered.

The GPS data were processed independently using two different software packages: the GIPSY software (GIPSY, 2017) and the PPP service provided by the Natural Resources of Canada (CSRS-PPP, 2017). In order to ensure a high accuracy, the outcomes of both tools were averaged in a way that points with height differences above 1.0 m were eliminated from the data (Schwieger et al., 2009). The final RMSE of the combined results reached 0.48 m and the availability rate was 53.5%. This can be explained by signal outages that occurred very often, especially in urban and forest areas. To start with an optimal accuracy below 0.1 m, an initialization phase of approximately 30 min was mandatory for every single track.

A total number of 14 million KGPS points were acquired along tracks encompassing a length of 66,000 km distributed across six continents. An overview of the collected GPS Ground Control Points (GCPs) for each continent is shown in Table 1. The GPS point collection attempted to acquire at least three GPS points per TanDEM-X pixel (approximately $12\,m \times 12\,m$ resolution on ground). GPS points within one pixel were averaged for further analyses.

2.2. GPS benchmark data

The reference data set "GPS on Bench Marks" is a highly accurate (millimeter to centimeter) set of GCPs which is measured and provided by the US National Geodetic Survey (NGS) for Northern America (GPS-on-BM, Mai 2017). These elevations are primarily used for geoid modelling. For our analysis, a total number of 23,961 points which were used (Fig. 1) were distributed across the United States. The coordinates of the points were provided in