Accuracy assessment of TanDEM-X IDEM using airborne LiDAR on the area of Poland

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Abstract: The TerraSAR-X add-on for Digital Elevation Measurement *(*TanDEM-X) mission launched in 2010 is another programme – after the Shuttle Radar Topography Mission (SRTM) in 2000 – that uses space-borne radar interferometry to build a global digital surface model. This article presents the accuracy assessment of the TanDEM-X intermediate Digital Elevation Model (IDEM) provided by the German Aerospace Center (DLR) under the project "Accuracy assessment of a Digital Elevation Model based on TanDEM-X data" for the southwestern territory of Poland. The study area included: open terrain, urban terrain and forested terrain. Based on a set of 17,498 reference points acquired by airborne laser scanning, the mean errors of average heights and standard deviations were calculated for areas with a terrain slope below 2 degrees, between 2 and 6 degrees and above 6 degrees. The absolute accuracy of the IDEM data for the analysed area, expressed as a root mean square error (Total RMSE), was 0.77 m.

1. Introduction

Multi-source data provides information on both the Earth's land surface and the elements of land cover – which play an important role in many fields, including hydrology, geomorphology, or ecology. In all these applications, the quality of the final product depends on the accuracy and the precision of the model used. In light of the above, evaluating the accuracy of a digital terrain model seems an important issue as it determines the application of the model.

Since the concept of a digital terrain model was introduced, a number of methods for constructing the model have been developed, including the technique based on interferometric measurement. The highly successful Shuttle Radar Topography Mission (SRTM) in 2000 was followed by the TanDEM-X mission which is currently implemented by the German Space Agency and the Airbus Defence and Space

company. TanDEM-X is another programme that uses the above-mentioned technique to construct a globally homogeneous digital surface model.

Apart from the mode and the range of the acquired data, the two missions differ primarily in terms of resolution and accuracy of the final product. According to specifications, the SRTM and TanDEM-X DEMs correspond to DTED-2 and HRTI-3 standards respectively.

The TanDEM-X mission used two twin satellites TerraSAR-X and TanDEM-X operating in the X band (a wavelength of 3.1 cm). Flying in a Helix formation (Krieger et al, 2007), the satellites collected interferometric data for the area between 90 degrees north latitude and 90 degrees south latitude. The TanDEM-X mission ended in 2014, but the data was processed until the second half of 2016 (Zink, 2015).The TanDEM-X final DEM with a resolution of 0.4'' (12 m on the equator) is calibrated based on the filtered observations captured by the Geoscience Laser Altimeter System (GLAS) onboard of the Ice, Cloud, and Land Elevation Satellite (ICESat) with an accuracy of approx. 0.4 m for flat terrain (González et al, 2010).The assumed absolute vertical accuracy of the TanDEM-X global DEM – expressed as LE90 – is 10 m and the relative vertical accuracy is below 2 m and 4 m for areas with a terrain slope greater than and smaller than 20 degrees, respectively. The relative vertical accuracy depends on the terrain characteristics and the geometry of the SAR scenes is used to generate the height model (Rizzoli et al, 2012; González et al, 2016).

The accuracy of the data collected by the TanDEM-X mission is object of research of many scientists around the world. The DEM accuracy for the territory of India assessed using GPS reference measurements and expressed as RSME, was 1.44 m for flat terrain, 4.9 m for hilly terrain and up to 8.2 m for mountainous terrain (Rinki et al, 2014; Pandit et al, 2014). For study areas in Canada, Russia and Australia, the accuracy was below 2 m (Wessel et al, 2014).

The height accuracy of the TanDEM-X IDEM was compared with the SRTM and ASTER data collected over the Aegean Islands (Vassilaki et al, 2015) and with ICESat points and points captured by GPS over the study areas in Canada, USA (Huber et al, 2012) and Iceland (Gruber et al, 2012).

The accuracy of the TanDEM-X data was also examined using data from airborne laser scanning, aerial photographs, SRTM and ICESat points (Rao, 2014; Balzter et al, 2016). The present article seeks to determine the absolute accuracy of the TanDEM-X Intermediate DEM based on data from airborne laser scanning of the southwestern territory of Poland.

2. Data and Study Area

The study area (Figure 1) covered a region with a surface area of approx. 1,000 km^2, situated in the south-western part of Poland (Lubuskie Voivodship and Lower Silesian Voivodship). The area included urban terrain, open terrain and forests. The study area was characterized by a high diversity of terrain features and denivelations reaching

Fig. 1. Study area

40 m. The highest elevations reached 330 metres above sea level, while the lowest areas were situated at an altitude of approx. 12 metres above sea level. The choice of the study area was dictated by the access to the TanDEM-X data for the territory of Poland.

The Intermediate DEM (IDEM) with a resolution of 0.4″ meeting the HRTI-3 (High Resolution Terrain Information) standard was provided by the German Space Agency (DLR) under the project "Accuracy assessment of a Digital Elevation Model based on TanDEM-X data". The TanDEM-X data subjected to accuracy assessment was generated based on 15 radar images captured by the Synthetic Aperture Radar (SAR) interferometer, using the bistatic Strip Map single polarization mode (HH) at a standard scene size of 30 km x 50 km. The angle of incidence for imaging ranged from 36 to 46 degrees. The satellite scenes used to generate the model were captured between 6 January 2011 and 28 February 2012 (Figure 2). The spatial reference system for the TanDEM-X height data is the WGS-84 system and its ellipsoid is a modification of the EGM96 geoid (Earth Gravitational Model). The TanDEM-X data analysed in this study is designed to generate a model of the land cover and land surface, thanks to the use of the X-band, the waves of which do not penetrate through vegetation or under the ground surface.

The IDEM is a product of the data acquired by the TanDEM-X mission exclusively from the first global coverage (single baseline), therefore it may be affected by an error associated with the phase unwrapping process. In addition to the model, the data set contains the following components: height error map (HEM), water indication mask (WAM), coverage map (COV), amplitude mosaic representing the mean value (AMP), amplitude mosaic representing the minimum value (AM2), consistency mask (COM), layover and shadow mask (LSM) and interpolation mask (IPM).

In accordance with the metadata attached to the data set, the mean height difference between the examined IDEM and the SRTM is 1.95 m at a standard deviation of
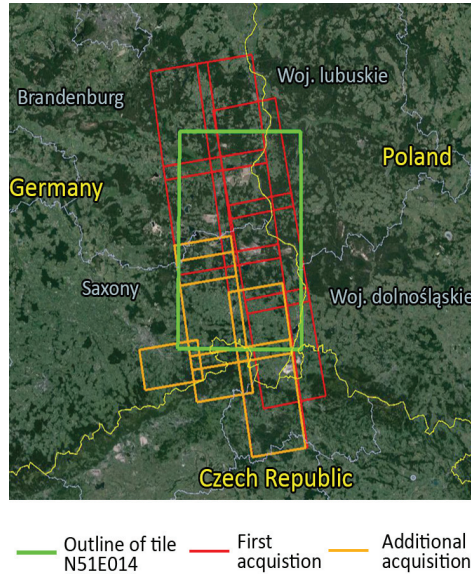
Fig. 2. Range of scenes used to generate the examined IDEM

5.96 m, while the mean height difference between the IDEM and a set of 3,157 ICESat points is 1.00 m at a standard deviation of 3.60 m.

As there is no information about the relative accuracy of the Intermediate Digital Elevation Model (IDEM) in the specification, this accuracy can be estimated by analyzing by-products of the TanDEM-X mission, i.e. information layers such as: height error map and water indication mask. Figure 3 shows the height error map for the TanDEM-X data. The map presents values of standard deviation calculated for each pixel of the model based on coherence and the number of SAR images used. The mean standard deviation for the TanDEM-X data is 0.85 m on average, with the highest values of standard deviation (max. 44 m) recorded in areas containing water bodies characterized by a lack of coherence.

The study uses the reference data captured via airborne laser scanning, which was provided by Poland's Central Office for Geodetic and Cartographic Documentation in the form of 1,152 classified point clouds in the .LAS format, version 1.2. Each point cloud corresponds to 1/16 of a section of a 1:10 000 scale topographic map (an area of approx. 1x1 km). The guaranteed accuracy of the point classification was min. 95%. The mean point cloud density was 4 points/m^2 and the mean height error did not exceed 0.15 m. The data was collected with the LiteMapper 6800i system within the framework of the project "National Information System for Protection Against Extreme Hazards" (ISOK) between 2011 and 2012. The data provided by the Central Office for Geodetic and Cartographic Documentation was elaborated in the rectangular coordinate system "1992" (PL-1992), and the normal height system "Kroonstad 86" (PL-KRON86-NH).
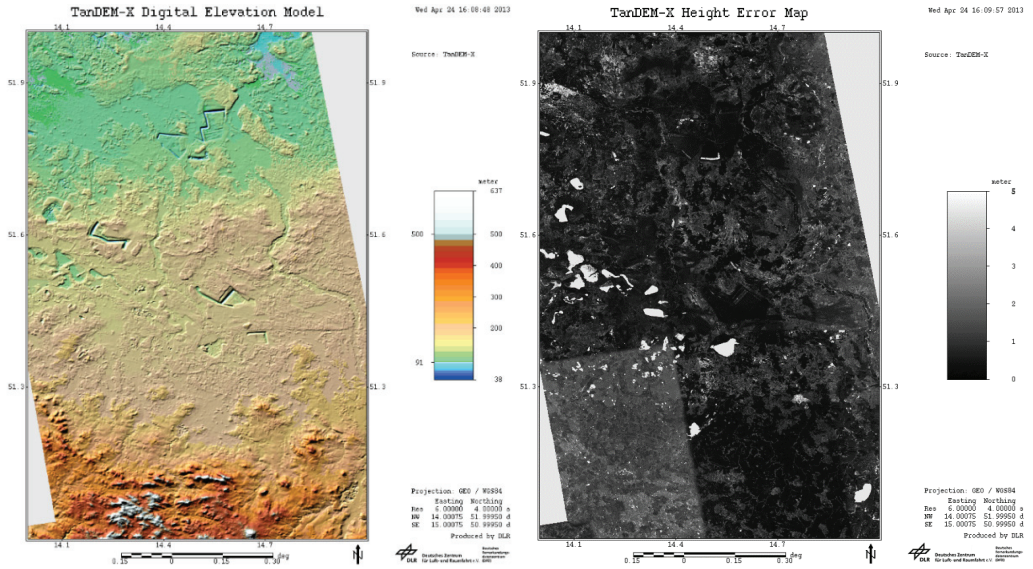
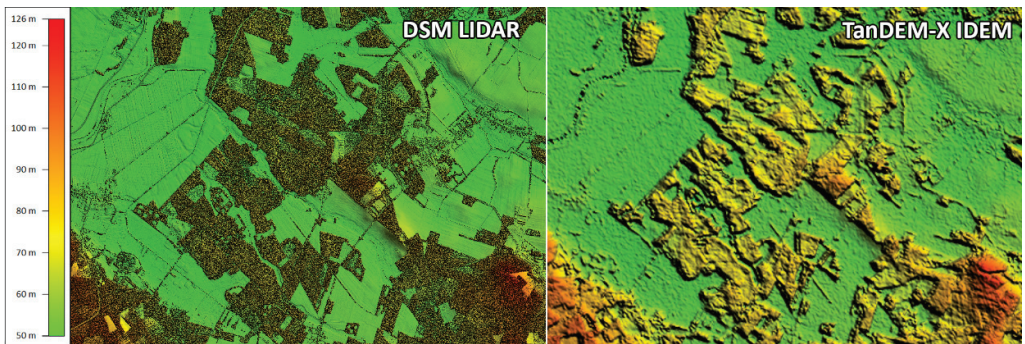Fig. 3. The IDEM and its height error map (provided by DLR)

Fig. 4. A piece of data used

3. Scope of work

The first stage of work involved appropriate preparation of the data. From the sets of points captured via airborne laser scanning, terrain points were selected which were later used for the interpolation of a digital terrain model (DTM) in a regular grid with an interval of 1m. The final DTM was characterized by height measurement accuracy expressed as a mean error amounting to 0.15 m for open terrain with little roughness and 0.25 – 0.30 m for forested terrain. The DTM was used to create a map of slopes
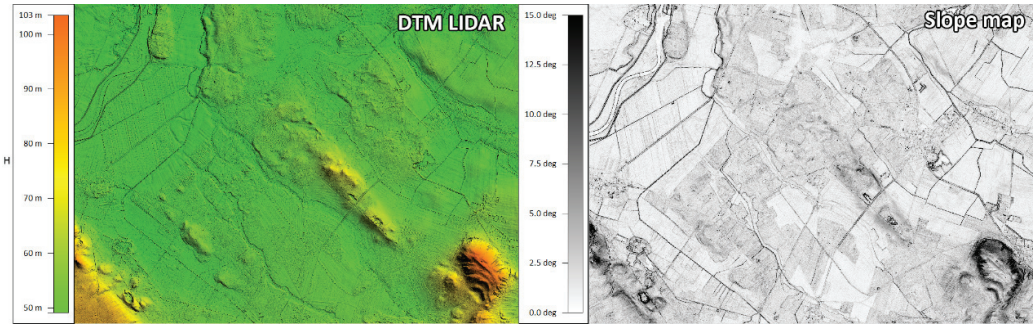
Fig. 5. Fragment of the generated map of slopes

containing three slope classes, i.e. areas with terrain slopes below 2 degrees, between 2 and 6 degrees and above 6 degrees (Figure 5).

Based on the ALS-derived digital terrain model, reference terrain profiles (Figure 6) were measured for each class and thus a precise reference data base was developed. The position of a profile point was calculated with an accuracy of 0.20 – 0.50 m in planimetry and 0.20 m in height. About 1,050 profiles with a total of 17,889 reference points were used for the analysis. A mean profile length was 240 m, and a mean distance between two adjacent points in particular profiles was 15 m.

The IDEM subjected to accuracy assessment was transformed into the flat rectangular coordinate "1992" system within the ArcGIS environment. To determine the normal heights of terrain profile points where their ellipsoidal heights were extracted from the examined model, one of the modules of the TRANSPOL software was used.
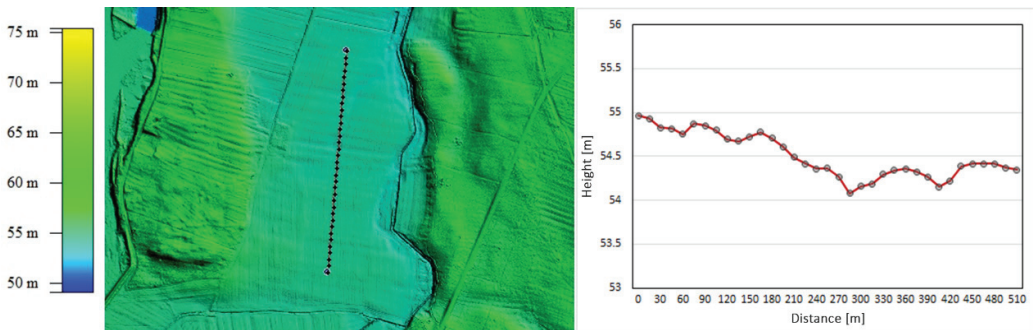

Fig. 6. Terrain profile measured based on the ALS-derived DTM

The objective of the research was to determine the absolute accuracy of the Intermediate DEM for the territory of Poland. Areas characterized by different slope

values, i.e. below 2 degrees, between 2 and 6 degrees and above 6 degrees were analysed, excluding urban and forested terrain. The accuracy of the TanDEM-X Intermediate model was measured in terms of the root mean square error (RMSE) calculated in accordance to the differences in height between the points in particular profiles, and the corresponding points interpolated from the examined model. In addition to determining the RMSE value, a statistical analysis was performed taking into account the minimum and maximum heights, standard deviation and the mean value of height differences. The analyses were performed using the modules of the SCOP++ software from Inpho.

4. Results and Discussion

The height differences between the ALS-derived DTM and the TanDEM-X Intermediate DEM were compared in 17,889 points measured along the profiles, among which 9,300 points were located in areas with a slope below 2 degrees, 7,468 – in areas with a slope from 2 degrees to 6 degrees, and 1,121 – in areas with a slope above 6 degrees. Figure 12 shows the differences in the height between the TanDEM-X model and the reference model for a selected profile consisting of 10 measurement points.

A regression analysis revealed a high value of the coefficient of determination $R^2 = 0.99$ (Figure 7) which indicates a considerable similarity between the ordinates in both models and, in consequence, a high accuracy of the TanDEM-X Intermediate DEM.
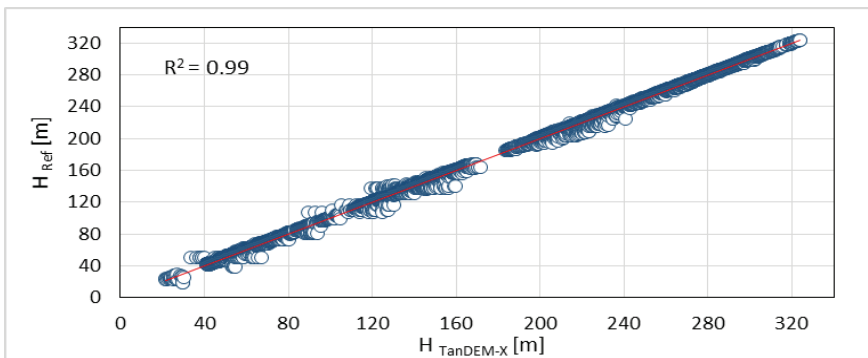

Fig. 7. Correlation of heights measured on the TanDEM-X Intermediate DEM
and on the model generated with airborne laser scanning data

Table 1 gathers the results of statistical evaluation of the differences between heights recorded on both models for areas characterized by different slope values, which, however, do not exceed 20 degrees. For the three examined classes, the accuracy

statistics of the IDEM are very similar and lead to identical conclusions. For areas with a slope below 2 degrees, the IDEM height showed a mean square error of 0.74 m, while for areas with a slope between 2 degrees and 6 degrees the RMSE was slightly higher and equaled 0.76 m. The highest RMSE value of 0.96 m was recorded for terrain with a slope above 6 degrees. The RMSE for the whole data set was 0.77 m. Distributions of height differences calculated for areas with different slope values shown in Figures 8, 9 and 10 are random and approximate a Gaussian distribution. The results obtained allow a conclusion that the IDEM deviates from the land surface by 0.3 m on average.

When analyzing the research findings, we reached a conclusion that the root mean square error of the TanDEM-X intermediate DEM for the study area depended only to a small extent on the terrain slope value, which did not exceed 20 degrees. In view of the above, another analysis of the measurement data set was performed to determine the absolute accuracy of the model, which was expressed as a linear error LE90 with the value of 0.85 m. The result obtained indicates that the absolute height accuracy for the IDEM is tenfold greater than that declared in technical specifications.

It should be noted that the statistics did not include about 2% of the reference points which were rejected as gross errors, i.e. the points with deviation values exceeding three times the value of standard deviation. The majority of errors were considered as a result of changes in land use which occurred over the time between the collection of the ALS data and the collection of the interferometric data, while the remaining errors were due to incorrect classification of the ALS data.

Table 1. Accuracy characteristic of the TanDEM-X IDEM for areas with different slope values

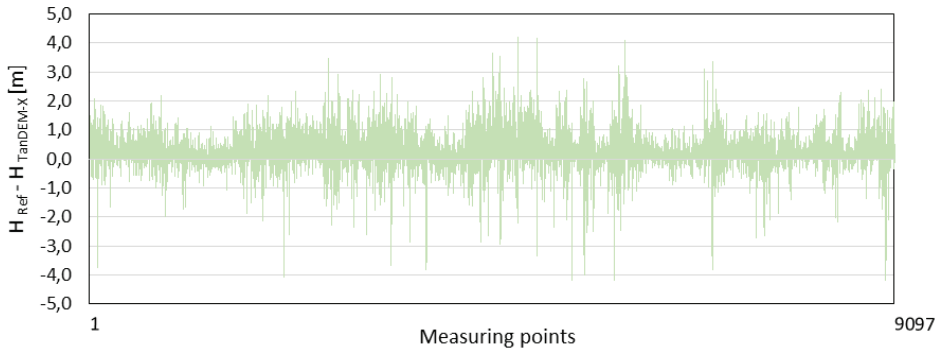| Slope values [degrees]	Number of profiles	Number of points in profiles	Average height difference [m]	RMSE [m]	Standard deviation [m]
Below 2	435	9097	0.30	0.74	0.51
Between 2 – 6	519	7298	0.32	0.76	0.50
Above 6	105	1103	0.34	0.94	0.60
Total	1059	17498	0.32	0.77	0.52

Fig. 8. Height differences between reference points for areas with a slope below 2 degrees
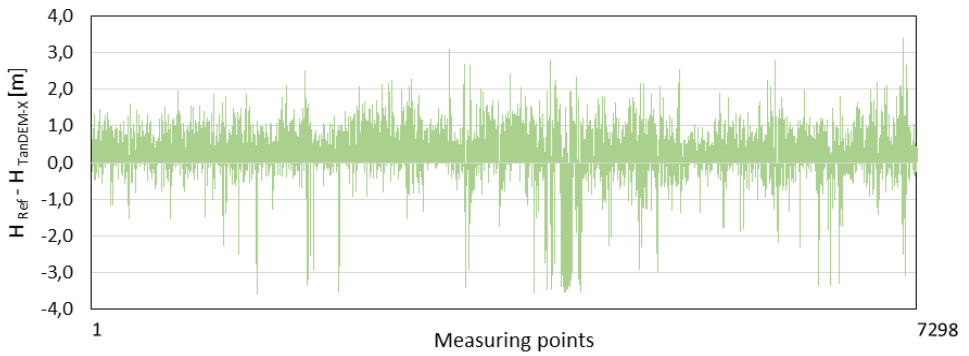

Fig. 9. Height differences between reference points for areas with a slope between 2 degrees and 6 degrees
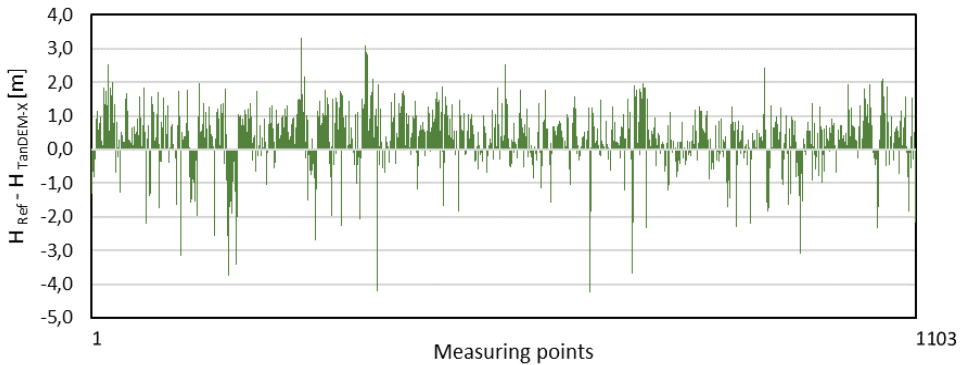

Fig. 10. Height differences between reference points for areas with a slope above 6 degrees

In the statistical assessment of the TanDEM-X IDEM accuracy, the random variable represented height differences between pairs of homologous points belonging to profiles measured on the ALS-derived model and interpolated from the IDEM. The most numerous random sample was the set of random variables for areas with a slope below 2 degrees, for which the standard deviation was 0.54 m. The least numerous random sample was recorded for areas with a slope above 6 degrees, for which the standard deviation was 0.72 m. The obtained values of standard deviations indicate a high level of repeatability of the results and the reliability of the analyses performed.

Figure 11 contains a graph showing the number of errors in particular intervals. The horizontal axis depicts the size of intervals, while the vertical axis shows the number of errors in those intervals. The distribution of height errors in the study area approximates a Gaussian distribution. The standard deviation of the height differences, defined as a random error, was 0.5 m for the entire data set (irrespective of the inclination of the terrain), while the systematic error was 0.3 m. Because of the roughness of the terrain, the differences in the time of obtaining the reference data and the TanDEM-X data and the accuracy of the reference data up to 0.15 m, the systematic error can be considered as negligible.
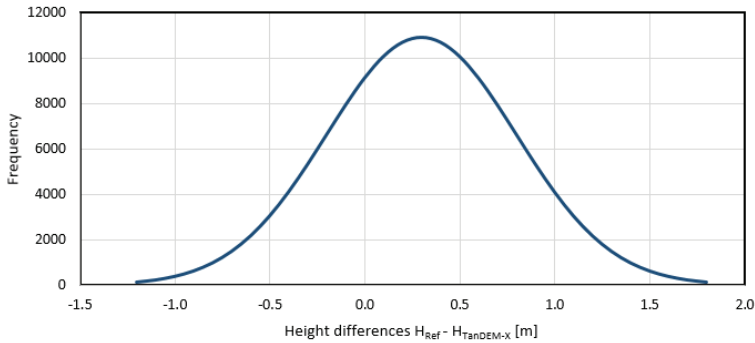

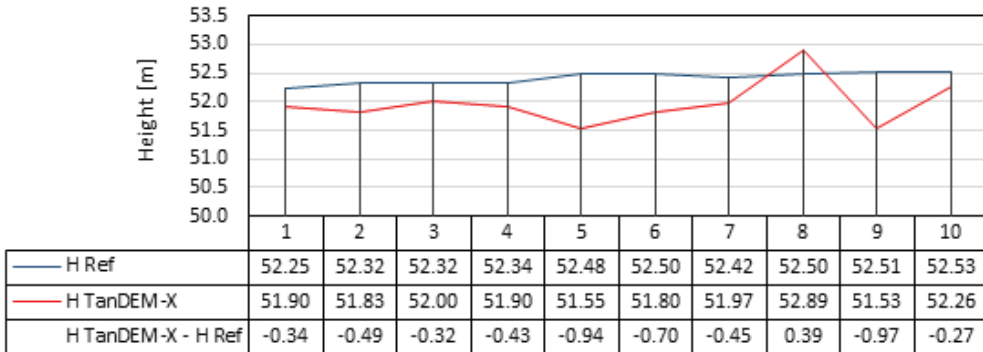Fig. 11. Distribution of errors appointed in reference points

	1	2	3	4	5	6	7	8	9	10
H Ref	52.25	52.32	52.32	52.34	52.48	52.50	52.42	52.50	52.51	52.53
H TanDEM-X	51.90	51.83	52.00	51.90	51.55	51.80	51.97	52.89	51.53	52.26
H TanDEM-X - H Ref	-0.34	-0.49	-0.32	-0.43	-0.94	-0.70	-0.45	0.39	-0.97	-0.27

Fig. 12. Height values of terrain profile points and points interpolated from the IDEM

5. Conclusions

This article presents one of the first results of accuracy assessment of the Intermediate DEM provided by the TanDEM-X mission over the territory of Poland. The studies have confirmed the initial assumptions concerning the absolute height accuracy of the Intermediate DEM. Based on the research findings, a conclusion can be made that the Intermediate DEM for the southwestern territory of Poland shows an absolute height accuracy of LE90 = 0.85 m for flat and hilly areas with a slope below 20 degrees.

The interferometric measurements performed during the TanDEM-X mission represent a valuable photogrammetric material and the quality of interferometric data acquired using the bistatic InSAR mode is considerably higher than the quality achieved during SRTM missions (Rizzoli et al., 2012).

It should be remembered that the quality of a model generated with interferometric measurements depends not only on the terrain slope, but also on the terrain coverage. In the present study, the reference points belonging to particular profiles were located exclusively in open terrain, covered mostly with low vegetation. Therefore, future studies should also examine the impact of various forms of land cover and terrain slopes exceeding 20 degrees on the accuracy of the Intermediate and Final DEM.

Acknowledgments

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