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ASSESSMENT OF THE VERTICAL ACCURACY OF SRTM-1″ DATA OVER THE TERRITORY OF POLAND USING THE RUNWAY METHOD

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Summary

The aim of this project was to estimate the accuracy of the Shuttle Radar Topography Mission (SRTM) digital elevation model over the territory of the Republic of Poland, using the centreline cross-sections of runways as reference data. This method is known as the runway method.
The statistical investigations were carried out based on the height differences between the SRTM and the reference data. For this purpose, 22 sections of the SRTM with 1 arcsecond of spatial resolution (SRTM-1″) and profiles of 30 runways were used. Data processing was performed using ArcGIS (Esri) software package. The study found that the SRTM-1″ had a –3.65 m magnitude elevation bias. The standard deviation and root-mean-square error (RMSE) of the elevation differences between the SRTM and the reference data reached the level of 1.88 m and 4.14 m, respectively. The obtained results are consistent with the investigations of the SRTM-3″ model conducted by other authors for the area of Poland and other countries. Overall, it can be confirmed that the SRTM-3″ model performs significantly better over flat areas than the SRTM-1″ in terms of RMSE of the vertical accuracy.

Keywords

SRTM • The Runway Method • Poland • DEM accuracy

1. Introduction

Digital elevation models (DEMs) are one of the well-known ways of representing the topography of the surface of the Earth. DEMs are created based on spatial data (i.e., x, y and z coordinates) plus an identification flag enabling the recognition of the kind of object that each point represents. One of the methods for acquiring the spatial data is through interferometric synthetic aperture radar (InSAR), which uses microwaves emitted and received by the radar, and the interferometric effect. The InSAR method was used to produce the world's first nearly global DEM. The product is known as the Shuttle Radar Topography Mission (SRTM) [Farr et al. 2007; JPL 2015]. The SRTM program concluded over 10 years ago, but interest in the SRTM data remains strong among numerous branches of science, including geomatics. Many studies demonstrated that the SRTM could be used to develop a topographical layer for small – to medium –scale maps suitable for various types of studies, including hydrographic, ecological and geomorphometric studies. Interest in the SRTM data has increased over the last few years because the custodian of the data decided to publish the full resolution SRTM dataset.

In this paper, we show the results of an investigation into the vertical accuracy of the SRTM-1″ model over the territory of the Republic of Poland using a relatively new method: the runway method (RWYM) [Becek 2008]. The RWYM uses airport runways as elevation reference features for several reasons, including the public domain availability of runway elevation data, their strictly observed technical parameters, their smooth and uniform surfaces and their almost ideally flat (i.e., horizontal) orientation. These characteristics are some of the key elements of the safety requirements for aircraft operations (take-offs and landings). In every country in the world, there is a dedicated government agency that is responsible for maintaining and disseminating information on the country's airports, including runways, to the public. There are also third-party services available that compile information on airports for several countries and present it online [Eurocontrol 2016, GEDTF 2017].

The dimensions of a typical runway are between 1,000 m and 4,000 m in length (on average, 2,500 m), and 15 to 60 m in width. The slope of a runway is generally below 1% [ICAO 2017]. And except for a very limited time only, runways are obviously free of any obstacles, including vegetation and anthropogenic structures.

The key feature of the RWYM is the error model it assumes. The error structure of this method assumes that the total DEM error is the sum of three statistically independent components, namely: the instrument-, target- and environment-induced components [Becek 2008]. This error structure is commonly accepted in land surveying and many other branches of science.

Accuracy estimates provided by the RWYM cover only the instrument-induced vertical error component. This is sufficient, because the target-induced component can be estimated using a simple formula, which reveals that the target-induced component equals zero over flat areas and does not depend on the resolution over flat surfaces. The environment-induced error is of the systematic type (i.e., bias) and mainly depends on the interaction between the electromagnetic waves used and type of land cover.

The vertical accuracy of the SRTM-3″ was previously investigated using the RWYM [Becek 2014]. This was done using a different set of runways, mostly located beyond the borders of the Republic of Poland. However, since the RWYM produces the instrument-induced error component only, the results do not depend on the resolution over the flat areas. Therefore, our working hypothesis is that the result achieved in Becek's investigation [2014] should be consistent with the result achieved in this study.

2. The Aim and Objectives of the Project

The aim of this project is to estimate the vertical accuracy of the SRTM-1″ – the highest resolution version of the SRTM elevation data product over the territory of the Republic of Poland – using the RWYM. The following objectives were pursued towards achieving the above aim:

1. Acquire the SRTM-1″ cells over the territory of Poland.
2. Acquire the runway elevation reference data.
3. Extract the elevations from SRTM-1″ along the centrelines of runways.
4. Calculate the corresponding elevations from "as-built" runway data.
5. Calculate the differences between the SRTM-1″ data and the reference elevation for all runways and all points along the centrelines.
6. Develop selected statistical characteristics of the elevation differences.

3. Previous Studies on the Vertical Accuracy of the SRTM

The most comprehensive investigations of the vertical accuracy of the SRTM data were conducted by NASA [Rodríguez et al. 2006]. The investigations were carried out by comparing the SRTM elevations with several reference elevations. These reference elevations were points, such as GPS points or transects along transportation lines; ICESat data (space-based LiDAR data) [Tulski 2014]; and photogrammetrically derived DEMs of higher resolution and accuracy. These investigations were carried out on all continents excluding Antarctica. This wide geographic spread of the reference data was designed to capture potential spatial component of the discrepancies between the SRTM and the reference data. The results were classified by the type of topography and land cover. All investigations clearly indicated that the vertical accuracy of the SRTM data was significantly higher than required by the SRTM project design. The SRTM-3″ was also investigated using the RWYM [Becek 2008, 2014]. The instrument-induced error of the SRTM-3″ was estimated at 1.55 m [Becek 2008] and 2.2 m [Becek 2014] (1 sigma root-mean-square error [RMSE]).

For the territory of the Republic of Poland, several investigations of the vertical accuracy of the SRTM-3″ were carried out [Karwel and Ewiak 2006]. The authors used test fields spread across 14 districts of the country. They found that RMSE for flat terrain and hilly terrain was 2.9 m and 5.4 m, respectively. Another study investigated the SRTM data using test fields located in northern, central and southern Poland [Zieliński and Chmiel 2007]. Table 1 shows a summary of their findings. As demonstrated, these results are consistent with the results of other authors.

Table 1. Summary of the vertical accuracy assessment (RMSE) of the SRTM-3″

	Slope [%]		
	0–10	**10–20**	**> 20**
Urban area	2.2–3.9 m	2.5 m	No data
Rural area	1.7–3.0 m	3.4 m	6 m
Forest	3.6–5.2 m	5.2 m	

Source: data reported in Zieliński and Chmiel [2017]

The accuracy of the SRTM-1″ was conducted by several teams. Two most comprehensive studies are mentioned here. The first study by Rodríguez et al. [2006] found that the RMSE error of the SRTM-1″ for the entire SRTM coverage is approx. 3.8 m (one sigma). Investigations conducted by Miliaresis G.C. [2007] on an area with highly developed topography found that the one sigma vertical accuracy error is 11.2 m, which is much higher than estimated in the previous study. However, this discrepancy is attributed to significant slopes present in the test area.

4. Error Sources of SRTM Data

Designers, developers and operators of the SRTM mission (i.e., NASA, German and Italian Space Agencies, DLR and ASI, respectively) have identified the following sources of errors in the SRTM data [Rodríguez et al. 2005]: static error sources and time-dependent error sources, including space-dependent errors because of the movement of the shuttle.

Static error sources remain stable during the entire data acquisition process. These error sources can be managed to some extent by careful calibration. Some of the time-dependent errors were caused by the instability of the space shuttle arm that hosted the SAR antenna. This instability was caused by short burns of the small rocket engines that controlled the orientation of the shuttle in space. Also, the SAR microwave phase drift contributed to the time-dependent errors. These error sources impacted the final product (i.e., the SRTM) by increasing the absolute elevation error, including its space dependency, and increasing the positioning, or geolocation, error [Rodríguez et al. 2006]. In the RWYM terminology, these error sources constitute instrument-induced errors. Note also that they do not depend on the target or the surface of the Earth.

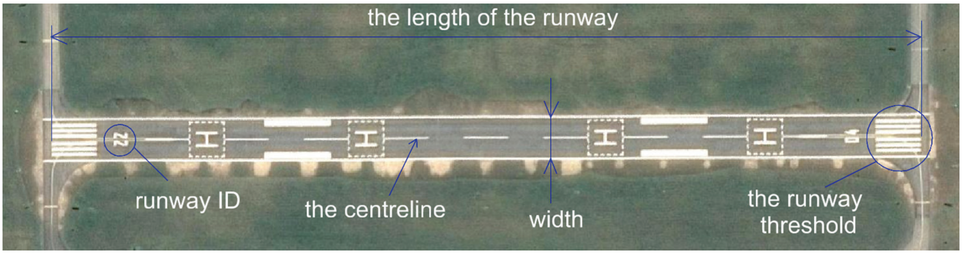
5. Data and Method

5.1. SRTM-1″ Data

The investigated SRTM-1″ data are referenced to the Earth Gravity Model 1996 and World Geodetic System 1984 vertically and horizontally, respectively. The vertical resolution, or quantisation level, is 1 m. The horizontal resolution is 1 arcsecond, which corresponds to approximately 30 m by 30 m at the Equator, but the longitudinal pixel size gradually gets smaller at latitudes above/below the Equator. The data are available online as a 1° by 1° tiles [USGS 2016]. In order to cover the entire territory of the Republic of Poland, 58 tiles were required. However, the reference data were available for 22 tiles only.

5.2. Reference Data

The RWYM uses the cross-sections of runways along their centrelines. These cross-sections were surveyed after the construction of a runway ('as-built'), typically using the spirit levelling method. The vertical accuracy of the cross-section is listed to be better than 0.25 m or 0.5 m for the 1st and 2nd class airports, respectively. The elevations of the breakpoints on the cross-section are published on the Airport Obstacle Charts Type A (AOC), which is available in the public domain. These charts were downloaded from the Eurocontrol European agency website [2016]. The charts are supplied to the agency by the relevant national agencies in charge of airports. The majority of the runways are 45 m or 60 m wide, and the average length of runways used in this study was 2,477 m (min/max: 600 m/3,690 m). The perpendicular cross-sections of the runways have a breakpoint at the centreline. This is the highest point in this type of cross-section. The lowest points on the perpendicular cross-sections are at the fringes of the runways. The height difference between the points on the centrelines and on the edges of the runways is at most 0.45 m. The estimated vertical accuracy of the centrelines is approximately 0.25 m. Figure 1 shows a satellite image of a runway, including some annotations.



Source: GoogleEarth®, www.google.pl/maps (accessed 5.01.2017)

Fig. 1. Satellite image of a runway at Darłowo airport, including some annotations

The runway reference data for the entire world are also available from the Global Elevation Data Testing Facility [GEDTF 2017]. The surface of the runway is, in most cases, smooth and made of a uniform material (i.e., asphalt or concrete). This is an additional feature of runways that makes them suitable for testing purposes [Becek 2008]. Figure 2 shows a fragment of one of the runways used in this study.

Overall, 30 runways located at 29 civilian and military airports across the country were used. The majority of the runways were oriented east to west. The lowest and highest located runways are Darłowo (4 m) and Katowice (302 m), respectively.

Figure 3 shows the location of the runways in Poland. Table 2 shows some of the technical details of the runways used in the study. The Reference Elevation a.m.s.l. column lists the mean elevation (above mean sea level) of the airport facility. It is provided here to illustrate the vertical range of locations of the airports used in this experiment only. This piece of data is available from the aeronautical documentations of each airport [Eurocontrol 2016]. It is not used in our calculations.

The runway profiles contained 3 to 11 breakpoints with known elevations. The locations of the profiles were verified by comparing the profile with the centreline of the runways as displayed on the Google Earth® satellite image.

Source: dlapilota.pl, http://dlapilota.pl/obrazy/port-lotniczy-olsztyn-mazury-pas-startowy-fot-port-lotniczy-olsztyn-mazury (accessed 5.01.2017)

Fig. 2. A terrestrial photograph of a runway

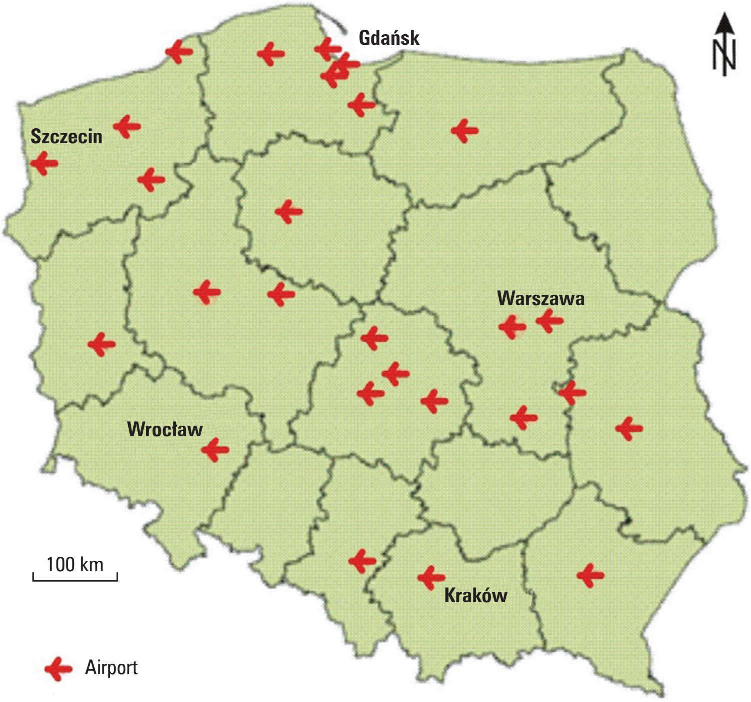


Fig. 3. Locations of airports used in the study

Table 2. Runways used as elevation references in this study

Runway	Reference elevation [a.m.s.l.]	Length [m]	Width [m]	Type of surface
Bydgoszcz	72	2500	60	asphalt/concrete
Cewice	151	2518	60	asphalt/concrete
Darłowo	2	600	30	asphalt/concrete
Dęblin	119	2500	60	concrete
Gdańsk	139	2800	45	asphalt/concrete
Gdynia	43	2500	60	concrete
Katowice	302	3200	45	concrete
Kraków	238	2550	60	concrete
Łask	190	2500	60	concrete
Łęczyca	119	2500	60	asphalt/concrete
Łódz	179	2500	45	asphalt/concrete
Malbork	5	2500	50	concrete
Mińsk Mazowiecki	177	2500	80	concrete
Mirosławiec	150	2500	45	asphalt/concrete
Olsztyn	138	2500	45	asphalt/concrete
Powidz	114	3515	60	concrete
Poznań Ławica	91	2504	50	asphalt/concrete
Poznań Krzesiny	83	2500	60	concrete
Pruszcz Gdański	4	1162	45	asphalt/concrete
Radom	185	1795	45	asphalt/concrete
Rzeszów	209	3200	45	asphalt/concrete
Szczecin	42	2500	60	asphalt
Świdwin	117	2500	60	concrete
Tomaszów Mazowiecki	184	2000	60	concrete
Warszawa Modlin	107	2500	45	asphalt/concrete
Warszawa Okęcie R1	107	2300	50	asphalt/concrete
Warszawa Okęcie R2	107	3690	60	asphalt
Wrocław	122	2503	58	asphalt/concrete
Zielona Góra	58	2500	60	concrete

Source: authors’ study

5.3. Method

The present study uses the RWYM [Becek 2008]. The RWYM method is founded on the fact that the vertical error of a DEM is made of three statistically and physically independent components or sources. The first component is the instrument-induced error source. This source, as the name suggests, produces measurement noise due to the imperfections of the measurement method used to generate the DEM, the instrument, and data processing (e.g., rounding off elevation to the nearest metre, InSAR vs LiDAR, photogrammetry, tachymetry). These errors are unavoidable and can be random, systematic or systematic of the random type.

The second error source – the target-induced error source – is due to the discretisation of a continuous surface by pixels of a certain size. The variance of the error for a given pixel can be calculated using the following formula in Equation (1) [Becek 2008]:

$$\sigma_T^2 = \frac{d^2}{12}\tan^2(s) \tag{1}$$

where:

d – pixel size,
s – the slope at a particular pixel.

The variance increases with the growing size of the pixel and the slope of the terrain. This component disappears for flat terrain (slope = 0°).

The third component is the environment-induced error source. It is common knowledge that both the medium (i.e., atmosphere or water) and land cover of the environment interact with electromagnetic waves. This interaction causes measurement errors. The impact of the environment can be corrected to some degree, but some residual error remains in the results. However, the 'atmospheric error' residual is much smaller than the instrument-induced errors.

Formally, the variance of the vertical error of a DEM can be written as per Equation (2) [Becek 2008]:

$$\sigma_{SRTM}^2 = \sigma_I^2 + \sigma_T^2 + \sigma_E^2 \tag{2}$$

where:

index I, T and E indicate the instrument-induced, target-induced and environment-induced error components, respectively.

It has already been stated that the target-induced component of the vertical error is equal to zero for flat surfaces. Therefore, measurements made over a flat surface will contain instrument-induced errors and environment-induced errors due to a particular set of dominant environmental parameters during the DEM measurements. Differences between the reference data and the SRTM data over flat surfaces will produce an estimate for the instrument-induced error, including errors caused by the atmosphere.

The RWYM uses 500 points on each cross-section of 30 runways as a reference elevation. The corresponding elevations were interpolated using the bilinear method from the coincidental tiles of the SRTM-1″.

The following sequence of steps was executed to estimate the instrument-induced SRTM-1″ error:

1. For each runway, the difference Δh_i was calculated:

$$\Delta h_i = H^i_{SRTM} - H^i_{REF},\ i = 1,\ldots,\ 500 \tag{3}$$

where:

H_{REF} and H_{SRTM} indicate the elevation of a corresponding point on the reference and on the SRTM cross-section, respectively.

2. For each runway, the mean difference $m\Delta_h$, and its variance ($\sigma^2_{\Delta h}$) according to Equation (4) and (5) were calculated:

$$m_{\Delta h} = \frac{\sum_{i=1}^{500} \Delta h_i}{500} \tag{4}$$

$$\sigma^2_{\Delta h} = \frac{\sum_{i=1}^{500} (\Delta h_i - m_{\Delta h})^2}{499} \tag{5}$$

3. In the final step, the *RMSE* was calculated using Equation (6):

$$RMSE^2 = m^2_{\Delta h} + \sigma^2_{\Delta h} \tag{6}$$

6. Results

Table 3 shows the basic statistics for the elevation differences between SRTM-1″ and reference elevations for 29 runways. The runway at Lublin airport was excluded from the study because it was constructed after the SRTM mission was completed.

Table 3. Statistics of the elevation differences for 29 investigated runways

Airport	$m\Delta_h$ [m]	Extreme differences [m]		σ [m]	RMSE [m]
		Min	Max		
Bydgoszcz	–4.43	–11.58	3.37	3.08	5.39
Cewice	–2.59	–6.30	1.47	1.56	3.02
Darłowo	–3.89	–5.81	–2.07	1.00	4.01
Dęblin	–3.64	–6.90	–0.72	1.46	3.92
Gdańsk	–3.27	–7.05	0.20	1.26	3.51
Gdynia	–5.26	–11.11	0.89	2.65	5.89
Katowice	–4.20	–6.84	–0.61	1.31	4.40
Kraków	–3.19	–8.07	0.77	1.55	3.55

Table 3. cont.

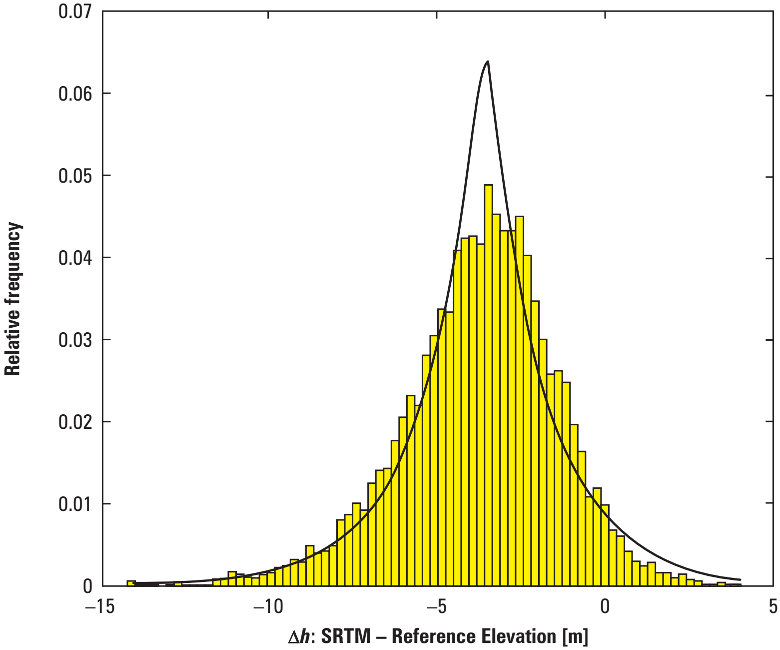
Airport	$m\Delta_h$ [m]	Extreme differences [m]		σ [m]	RMSE [m]
		Min	Max		
Łask	–3.54	–8.84	0.78	1.84	3.99
Łęczyca	–3.77	–8.09	1.31	1.81	4.18
Łódź	–3.75	–8.65	0.18	1.79	4.15
Malbork	–4.21	–10.25	–1.44	1.46	4.46
Mińsk Mazowiecki	–4.83	–12.64	0.47	2.55	5.46
Mirosławiec	–3.93	–8.11	0.80	1.73	4.30
Olsztyn	–2.31	–6.85	0.99	1.54	2.77
Powidz	–3.16	–7.70	1.94	1.96	3.71
Poznań Krzesiny	–2.79	–8.27	2.37	2.23	3.57
Poznań Ławica	–2.84	–9.12	4.24	2.24	3.62
Pruszcz Gdański	–1.26	–5.55	2.85	1.98	2.35
Radom	–4.05	–8.94	0.21	1.78	4.42
Rzeszów	–3.87	–8.49	0.87	1.98	4.35
Szczecin	–3.57	–6.76	0.08	1.62	3.92
Świdwin	–2.34	–6.00	–0.12	1.12	2.59
Tomaszów Mazowiecki	–5.65	–8.84	–1.43	1.73	5.91
Warszawa Modlin	–3.83	–11.06	–0.57	1.93	4.29
Warszawa Okęcie R1	–5.71	–11.23	1.60	2.56	6.26
Warszawa Okęcie R2	–5.47	–14.12	3.23	3.08	6.28
Wrocław	–2.57	–8.07	2.02	2.37	3.50
Zielona Góra	–1.94	–6.47	0.83	1.49	2.44
Mean	–3.65	–	–	1.88	4.14

Source: authors' study

Figure 4 shows a histogram of the height difference Δh for all runways. The theoretically correct (for this kind of random variable) Laplace probability density function (PDF) is also shown. The PDF was drawn based on the parameters estimated from the height differences for all runways. It appears that the histogram reasonably fits the theoretical PDF.

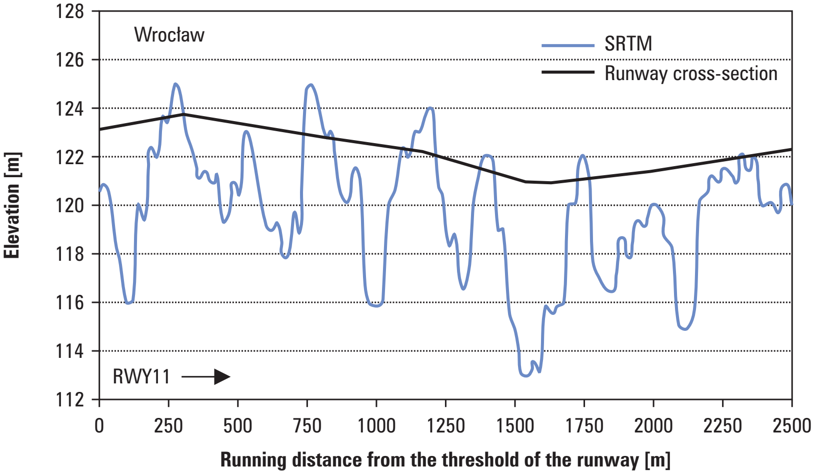
The mean value of the height difference based on all runways is –3.65 m, and the standard deviation is 1.88 m (relative error). Hence, in Equation (6), the *RMSE* (absolute error) is 4.14 m (or 8.11 m at the 95% confidence level).

Figure 5 shows an example of both the SRTM-1″ and as-built cross-sections of the runway at Wrocław airport. Some underestimation of the real profile of the runway is clearly visible. The amplitude of the SRTM-1″ data on this profile reaches approx. 9 m, while the variation in height of the real surface of the runway is approximately 3 m.



Source: authors' study

Fig. 4. Histogram of the difference Δh = SRTM minus reference elevations. The theoretical Laplace probability density function is also shown



Source: authors' study

Fig. 5. The SRTM-1″ and as-built cross-section of runway at Wrocław airport

7. Conclusions

As a result of the present study into the accuracy of the SRTM-1″ elevation data over the territory of the Republic of Poland using the RWYM, we have reached the following conclusions:

1. There is a systematic error or elevation bias in the data in the order of –3.7 m. This figure is exactly the same as obtained in a different study [Karwel and Ewiak 2006]. However, the bias identified during a separate study using runways mainly located outside Poland [Becek 2014] was found to be –1.7 m. We speculate that this significant discrepancy may be an effect of a slowly varying spatially explicit (regional to continental) error component in the SRTM data, which this study could not identify.
2. The standard deviation of the SRTM-1″ is 1.88 m. This is approximately twice as large as ~1.2 m (found in the SRTM-3″ model) [Karwel et al. 2006]. This discrepancy is caused by the fact that the SRTM-3″ was developed by the averaging (or decimation) of the SRTM-1″ [Becek 2007]. For this reason, the standard deviation of the elevation differences of the SRTM-3″ is smaller by a factor of $\frac{1}{\sqrt{n}} = \frac{1}{3}$, where n is the number of elements taken for the averaging. In the case of the SRTM-3″, there were 9 elements averaged from the SRTM-1″ for every pixel of the SRTM-3″. Hence, the standard deviation of the differences of SRTM-1″ should be 3 times higher, i.e., approximately 3.6 m. On the other hand, this study found that the standard deviation of the elevation differences is 1.88 m. This is significantly smaller than the hypothetical 3.6 m. However, this difference is most likely due to the high frequency damping effect of the interpolation procedure, which was performed to calculate the elevation of cross-section points from the SRTM-1″ tiles.
3. The RMSE was found to be 4.14 m. The corresponding value in Karwel et al.'s study [2006] and Becek's study [2014] was 3.8 m and 2.8 m, respectively. The higher RMSE for the SRTM-1″ means that the SRTM-3″ performs better than the SRTM-1″ over flat areas (because of the averaging effect). However, the higher RMSE for the SRTM-1″ is also partially due to the higher bias over the territory of Poland as suggested in Conclusion 1.
4. Although the SRTM-3″ performs better for flat areas, the superiority of the SRTM-1″ model is revealed in rough terrain, with the target-induced cases of 0.

As outlined in the introduction to the RWYM, this method accounts for the instrument-induced vertical error component only. Since the target-induced component changes from pixel to pixel (it is dependent on the slope of the terrain), it is incorrect to claim the vertical accuracy of the SRTM, without specifying a particular point on the surface.

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