Monika Badurska*

Orthorectification and Geometric Verification of High Resolution TerraSAR-X Images**

1. Introduction

TerraSAR-X is a German radar satellite that has been launched in 2007. It is the first satellite which was built in a Public Private Partnership in Germany between the German Aerospace Center (DLR) and EADS Astrium. TerraSAR-X is a side-looking X-band synthetic aperture radar (SAR) for scientific and commercial use. TerraSAR-X products are used for the application for map generation, terrain analysis and monitoring purposes. The other applications of TerraSAR-X include environmental planning, land cover mapping, natural resource exploration, regional and urban development, crisis response and relief, insurance and risk assessment, as well as applications in border control, security, intelligence and defence [5]. Radar data are registered in the side-looking imaging mode and the view angle of SAR image is much wider than in case of optical image. This leads to a great influence to geometric distortion of SAR image. Consequently, it is very important for SAR application to rectify geometric distortion and create orthoimage [1]. Additionally in order to evaluate the usufulness of TerraSAR-X data for the generation of various maps, the geometric accuracy of the SAR data should be analysed. The main aim of the study was ortorectification of raw TSX images in the SSC format and verification of geometric presion of geocoded, basic image products in the EEC format.

2. TerraSAR-X Basic Image Products

The instrument timing and pointing of the electric antenna of TerraSAR-X can be programmed allowing numerous combinations [3]. The system was designed

* AGH University of Science and Technology, Faculty of Mining Surveing and Environmental Engineering, Krakow, Poland
** The study was conducted under the research project no. NN526243335 financed by the Ministry of Science and Higher Education

to register in four imaging modes and different polarisation from medium to high resolution mapping. The following imaging modes are defined for the generation of basic products: High resolution SpotLight (HS), SpotLight (SL), StripMap (SM) and ScanSAR (SC) mode. There are two variants of sliding spotlight mode with different values for azimuth resolution and scene size: Spotlight (SL) and High resolution Spotlight (HS). Table 1 shows the basic parameters of the TerraSAR-X imaging modes. Beam steering enables observation in different incidence angles. Within the azimuth and ground range resolution ranges, the first resolution corresponds to the smallest given incidence angle, while the second one refers to the largest given incidence angle [6, 8].

Table 1. Main characteristics of the each acquisition mode

Parameters	High resolution SpotLight	SpotLight	StripMap	ScanSAR
Scene extension or Swath width	5 km × 10 km	10 km × 10 km	30 km	100 km
Incidence angle	20°–55°	20°–55°	20°–45°	20°–45°
Azimuth resolution	1.1 m (2.2 m)*	1.7 m (3.4 m)*	3.3 m (6.6 m)*	18.5 m
Ground range resolution**	1.48–3.49 m (55° ... 20° incidence angle)	1.48–3.49 m (55° ... 20° incidence angle)	1.7–3.5 m (45° ... 20° incidence angle)	1.7–3.5 m (45° ... 20° incidence angle)

* Respectively for single and dual polarization.
** Only for a spatially enhanced product (SE).

The SAR raw data are processed to basic image products by the TerraSAR-X Multi Mode SAR Processor (TMSP), which has beed developed by DLR [5]. The TerraSAR-X products are different depending on the geometric projection and processing level:

- **Single Look Slant Complex (SSC) –** a basic single look product of the focused radar signal in slant range geometry. Data is represented as complex numbers containing information about intensity and phase of registered signal. This kind of data is necessary in case of SAR interferometry (InSAR).
- **Multilook Ground Range Detected (MGD) –** a multilook detected product with reduced speckle after a simple polynomial slant to grant projection using a WGS84 ellipsoid and an avarage terrain height.
- **Geocoded Ellipsoid Corrected (GEC) –** a multilook detected product after the ellipsoid correction, projected and resampled to UTM (or UPS in polar regions). The ellipsoid correction does not consider a DEM but WGS84 is used as geodetic reference assuming one average terrain height.

- **Enhanced Ellipsoid Corrected (EEC) –** a multilook detected product after the terrain correction, projected and resampled to UTM (or UPS). All terrain distortions are corrected using a DEM, usually SRTM.
- **Geocoded Terrain Corrected (GTC) –** a multilook detected product after the terrain correction, to which an external high resolution DEM and ground control points are used. As other detected products, it is projected and resampled to UTM or UPS.

Depending on the time delay between acquisition and processing, one of the orbits can be used for the processing of basic products: predicted (±10 m), rapid (±2 m) or science (±20 cm). All detected products can be delivered as a radiometrically or a spatially enhanced product. The radiometrically enhanced product (RE) is optimazed with respect to radiometry while the spatially enhanced product (SE) is designed for the highest possible square ground resolution. The resolution of the first one is worse in case of significant speckle reduction by averaging of bigger number of looks (5 to 7).

3. SAR Geocoding

In order to use SAR images in many application connected with map generation and terrain analysis, their geometric distortions must be eliminated by applying a proper geometric correction or genereting a radar orthoimage in a defined map projection. Due to the side looking geometry of SAR system, it is characterized by completely different geometric properties from optical systems. Topography has significant influence on the geometric and radiometric properties of SAR images [2]. The most important local image distortions, cause by topographic difference, are foreshortening, layover and shadow. By the knowledge of the acquisition geometry of SAR image with a digital elevation model (DEM) of the imaged area, the process of terrain geocoding is used to transform an image into a common reference map geometry [7].

The Range-Doppler approach primarily discusses the relationship of image points and target points from the view of SAR imaging geometry [1]. In the rigorous Range-Doppler approach, the orthorectification process is a backward transformation, converts the position of the backscatter elements into slant range image coordinates. This transformation requires position and velocity vectors of both sensor and backscatter elements as well as Doppler frequencies and pulse transit times used for SAR image processing. For each backscatter element with a corresponding estimated sensor position, the slant range R_S and the Doppler frequency f_D is computed on the basis of Range equation (1) and Doppler equation (2).

Therefore:

$$R_S = \sqrt{(\vec{S}-\vec{P})\cdot(\vec{S}-\vec{P})} \tag{1}$$

$$f_D = \frac{2 f_0}{c} \frac{(\vec{v}_P - \vec{v}_S)\vec{R}_S}{|R_S|} \tag{2}$$

where:

$\vec{S}$, $\vec{P}$ – spacecraft and backscatter element position,
$\vec{v}_S$, $\vec{v}_P$ – spacecraft and backscatter element velocity,
R_S – slant range,
f_0 – carrier frequency,
c – speed of light.

4. Used Data

The analysed SAR data set was recorded by TerraSAR-X in the high resolution Spotlight mode with HH polarization. The main purpose of the study was to investigate the potential of high-resolution SAR data in the context of urban application, therefore all TerraSAR-X images were acquired over the city of Krakow. Part of the data was provided as a raw, single look product in slant range geometry (SSC) and the rest as a multilook detected product after the terrain correction (EEC). All of them have a science orbit accuracy. In case of EEC data, it was processed for the highest ground resolution as a spatially enhanced products (SE). The images were acquired with the different acquisition parameters, various incidence angles and various orbits: ascending (ASC), descending (DSC). Table 2 illustrates the acquisition dates and information about image parameters.

Table 2. Specification of used TerraSAR-X data

Parameters	TSX-1	TSX-2	TSX-3	TSX-4	TSX-5	TSX-6
Date of acquisitions	2009.10.11	2009.10.16	2009.10.27	2010.03.11	2010.10.22	2010.11.06
Type of orbit	DSC	DSC	DSC	ASC	ASC	DSC
Elevation beam identification	Spot_060	Spot_030	Spot_030	Spot_049	Spot_079	Spot_090
Incidence angle [°]	43.2	30.9	30.9	39.0	49.3	52.5
Processing level	EEC	SSC	SSC	SSC	EEC	EEC
Type of product	SE	–	–	–	SE	SE
Polarization	HH	HH	HH	HH	HH	HH
Ground range resolution [m]	1.74	2.29	2.29	1.87	1.58	1.51
Azimuth resolution [m]	1.1	1.1	1.1	1.1	1.1	1.1

It is worth mentioning, that four TerraSAR-X sets were registered in very rough atmospherical conditions, during complete or partial cloudiness and very poor visibility. In October 2009, due to snow or rain with snow, the conditions were definitely the worst. Registraction of optical images at that time would have been impossible.

The data used here were registered within *The use of high resolution TerraSAR-X data for urban mapping* project carried into effect as a part of TerraSAR-X Science Service System in DLR programme.

5. Single Look Slant Complex Data Processing

The aim of complex SSC data processing was radar orthoimage generation with resolution parameters accurate for urban areas classification process and filtered in respect of speckle effect reduction. Works related to SSC data processing included the process of synthesis of SAR images, their filtering and radiometrical and geometrical correction with accuracy assessment. In the picture (Fig. 1) a raw TSX-2 image, before applying multilooking, is shown.

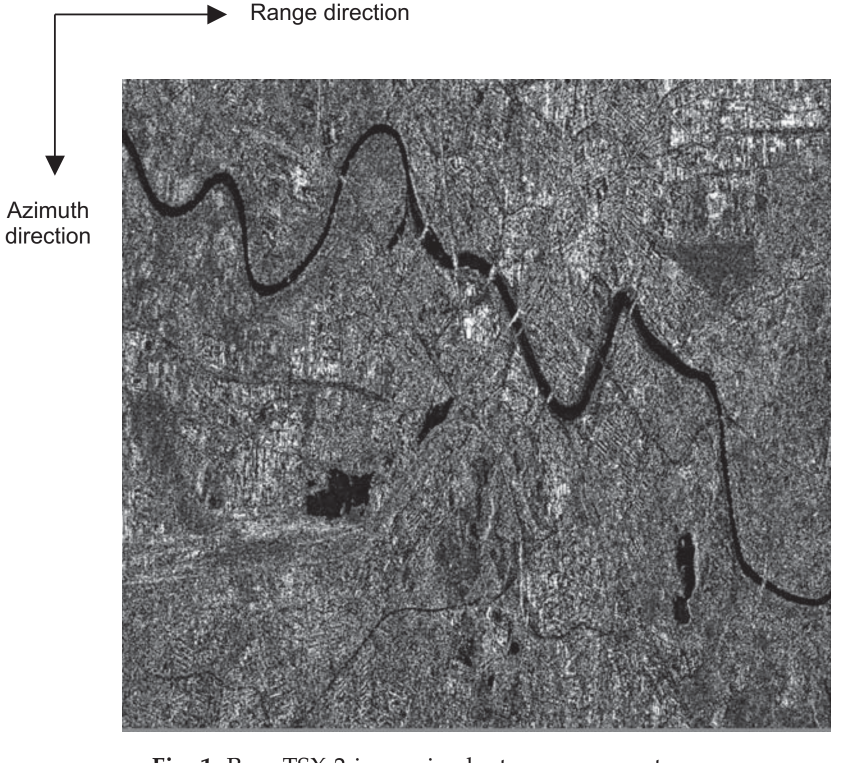

Fig. 1. Raw TSX-2 image in slant range geometry

All basic TerraSAR-X products are processed and delivered in radar brightness β_0. Radiometrical correction was run in order to minimalize radiometrical differences caused, among other things, by the influence of terrain topography and local angle on backscatter coefficient. Within conducted correction the pixel values were expressed in form of normalized backscatter coefficient Gamma Nought γ_0. Whereas in order to reduce the speckle effect, an adaptive filter Lee as well as De Grandi filter were used for multitemporal data. In this study only works related to orthorectification process of TerraSAR-X in SSC form and geometrical verification of products delivered by the producer are described. The diagram below shows particular stages of SSC data processing (Fig. 2).

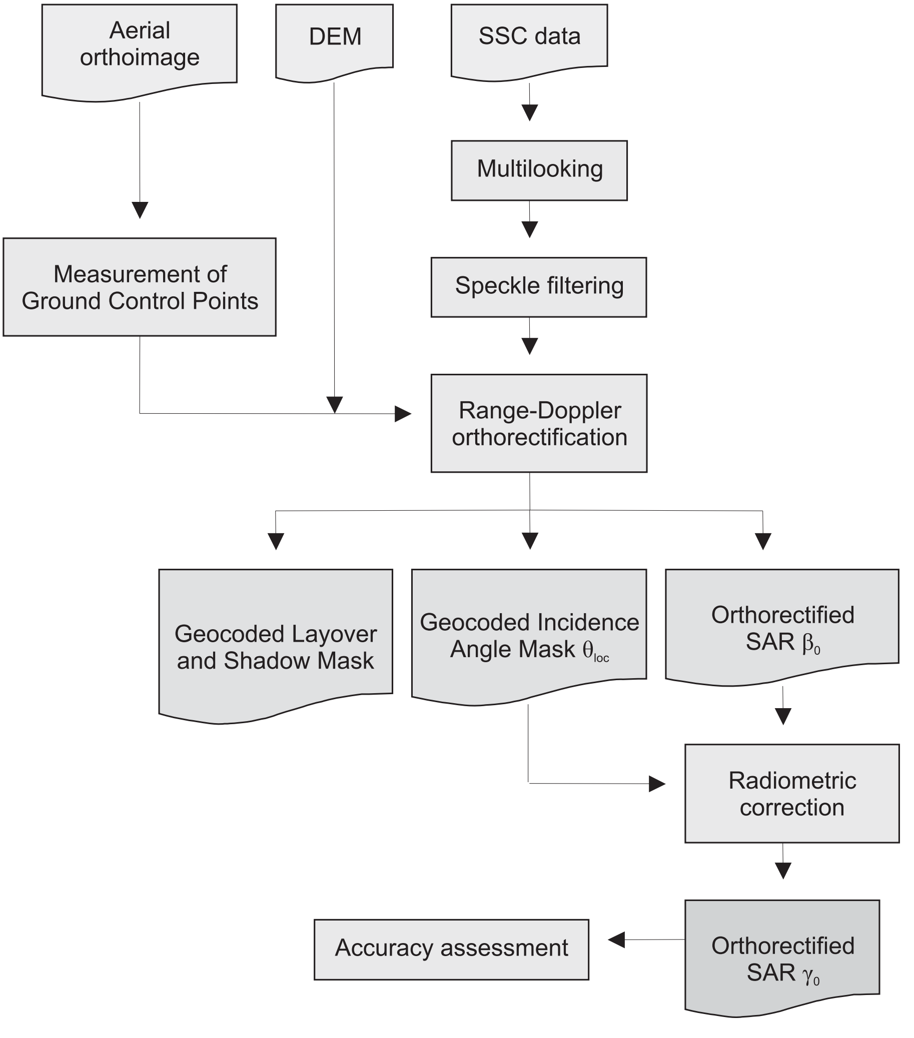

Fig. 2. Block diagram explaining particular stages of SSC data processing

6. Geometric Rectification

The rectification procedure was performed on data in the SSE format and based on the range-Doppler approach in SARscape software. Unfortunately, the correction process in that software takes place without obtaining information about orthorectification accuracy, providing only information about residual errors of ground control points used (GCPs). In connection to that, in order to verify the accuracy of orthorectification for every generated radar orthoimage additional accuracy analysis was performed. The source of ground control points necessary for orthorectification and check points used for accuracy assessment was an aerial orthoimage from 2006 with 25 cm pixel. Depending on the scene (from ascending or descending orbit) about 40 terrain details on the radar image and the referring aerial orthoimage were measured. Then, all identified points were divided into ground control points and check points. While choosing attention was paid to their steady placement within the radar scene and height value. The choice of ground control points on radar images is much more difficult than in case of optical images. The very specificity of SAR images is the problem, especially side--looking image geometry causes different imaging of particular land cover elements. It is worth remembering, that a radar image is not a photograph and while interpreting it, attention has to be paid to basic mechanisms of microwave beam scatter. It is very significant in case of urban area with numerous buildings. Road corners, pavements, playing fields or parking spaces, situated always on the surface of the terrain, were chosen as ground control points (and check points). During control points identification one has to be aware of distortions occuring in SAR images, such as foreshortening, layover and shadow, connected to geometry of registering and the terrain shape. It is appropriate if ground control points are located in open spaces, not surrounded by any high objects (trees or buildings).

The geometric quality of ortorectified SAR images depends on the height accuracy and resolution of the DEM in combination with the type of terrain and the incidence angle [4]. An important influence has also the accuracy of the type of orbit, but it was revealed that the pixel location accuracy in case of using rapid and science orbit was almost the same [3]. The influence of the quality of the digital elevation model was checked. The ortorectification process was performed using two available digital elevation models:

1) DEM LPIS – model with a grid size of 1 m, extracted from stereo aerial photography at the scale of 1:13 000. The images were acquired within the project of Land Parcel Identification System in 2003. The height accuracy of the model is defined on the level of 0.6 m.
2) DTED-2 – Digital Terrain Elevation Data for level 2 with a grid size of 30 m, extracted from existing topographic maps at the scale of 1:50 000. The height accuracy of the model is defined on the level of 1/3 of the contour interval.

Additionally, the influence of amount of ground control points on the results of ortorectification was also analysed. The last part of the work presents verification of geometric precision of geocoded EEC product generated by distributor.

7. Accuracy analysis

Within this study the influence of number of used ground control points as well as the influence of elevation model accuracy on the results of orthorectification were measured. Because in theory, in case of Range-Doppler model, using only one adjustment point is enough to improve the level of unaccuracy of the orbit, the accuracy of orthorectification was checked appropriately for one, three, five and seven ground control points (for TSX-2 and 3 data also for nine points). For both elevation models (DEM LPIS and DTED-2) the same sets of points were used. The following tables (Tabs 3–5) show detailed accuracy analysis.

Table 3. Accuracy analysis of TSX-2 orthoimage using different numbers of ground control points and DEM LPIS or DTED-2 models

Number of GCPs	DEM LPIS				DTED-2			
	n	RMS_X [m]	RMS_Y [m]	RMS_{XY} [m]	n	RMS_X [m]	RMS_Y [m]	RMS_{XY} [m]
1	36	1.82	1.23	2.20	39	2.13	1.63	2.68
3	28	2.34	1.97	3.06	30	2.04	2.54	3.25
5	29	3.09	1.06	3.27	30	2.74	1.58	3.16
7	29	3.45	1.58	3.79	29	3.41	1.86	3.88
9	24	3.32	2.25	4.01	26	3.26	2.43	4.07

n – number of used check points.

Table 4. Accuracy analysis of TSX-3 orthoimage using different numbers of ground control points and DEM LPIS or DTED-2 models

Number of GCPs	DEM LPIS				DTED-2			
	n	RMS_X [m]	RMS_Y [m]	RMS_{XY} [m]	n	RMS_X [m]	RMS_Y [m]	RMS_{XY} [m]
1	35	1.78	1.24	2.17	38	2.17	1.07	2.42
3	29	2.40	2.12	3.20	31	2.08	2.60	3.33
5	29	3.03	1.09	3.22	30	2.80	1.75	3.30
7	29	2.29	1.17	3.49	30	3.51	1.69	3.89
9	25	3.30	2.10	3.91	26	3.36	2.21	4.02

n – number of used check points.

Table 5. Accuracy analysis of TSX-4 orthoimage using different numbers of ground control points and DEM LPIS or DTED-2 models

Number of GCPs	DEM LPIS				DTED-2			
	n	RMS_X [m]	RMS_Y [m]	RMS_{XY} [m]	n	RMS_X [m]	RMS_Y [m]	RMS_{XY} [m]
1	30	3.03	1.94	3.60	27	3.15	1.86	3.66
3	31	2.32	2.17	3.18	31	2.11	2.48	3.26
5	33	2.71	2.35	3.59	32	2.55	2.65	3.68
7	33	3.20	1.71	3.63	32	3.40	1.48	3.71

n – number of used check points.

High accuracy of orthorectification using only one point for interferometrical pair TSX-2 and TSX-3 was a big surprise. In that case, within the increase of points number, the correction accurary decreased. Unfortunately that was not true for TSX-4 scene, where the accuracy when using only one point turned out to be 3.60 m. It is worth emphasizing though, that TSX-2 and TSX-3 images were obtained from the descending orbit, while the TSX-4 image came from the ascending orbit. Literature research however does not display, that the type of orbit has any effect on geometrical data accuracy [3].

Based on the tests performed one can conclude, that increasing the points number does not increase accuracy of generated radar orthoimage, whereas an optimal solution seems to be using 3 to 5 ground control points.

The accuracy value of orthoimages generated based on terrain numerical models DEM LPIS and DTED-2 were very similar. Using an accurate elevation model DEM LPIS improved the results of orthorectification only slightly. The analysis of deviation on check points showed, that in case of an orthoimage generated using the DTED-2 model, the deviation value of particular check points have the same value throughout the whole scene, regardless of terrain surpassing (Fig. 3). Whereas for the orthoimage generated using the DEM LPIS model, the deviation value is more sensitive to terrain shape and it is the smallest in case of flat urban area (Fig. 4).

The TSX-2 and TSX-3 orthoimages, generated only based on one point, were subject to additional analysis. 15 areas were vectorized on the aerial orthoimage. Then, the same areas were projected onto radar orthoimages and an error vector on the X and Y axis was measured. The deviations measured confirmed the analysis performed based on check points. Singular, increased deviations occurred in case of the orthoimage generated with DTED-2 model.

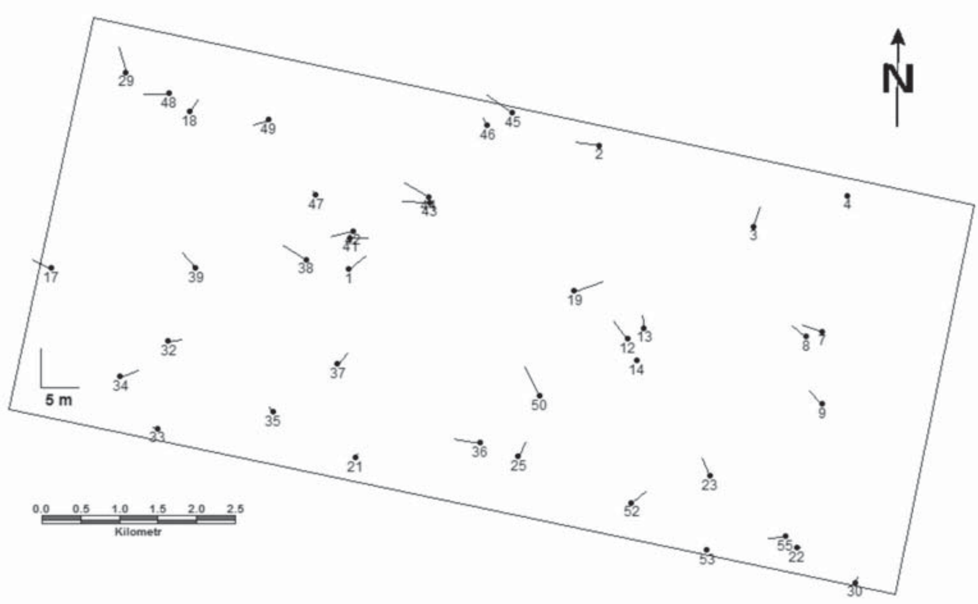

Fig. 3. Check points deviations for TSX-2 orthoimage generated based on one point and DTED-2 model

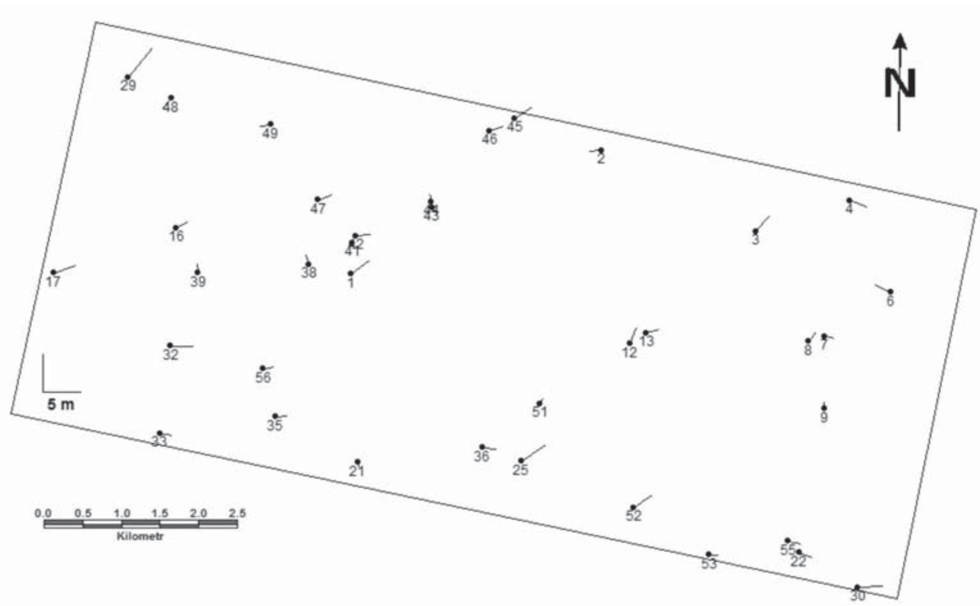

Fig. 4. Check points deviations for TSX-2 orthoimage generated based on one point and DEM LPIS model

8. Verification of Geometric Precision of EEC Product

Processing of images provided by the producer in EEC format meant reducing the speckle effect and performing radiometrical correction. Additionally, verification of accuracy of provided images was performed. The analysis was conducted analogically to accuracy assessment of orthorectified SSC data. Throughout the whole scene check points were measured (Fig.5). In most cases they covered the points used in SSC data analysis. In table (Tab. 6) deviation values for EEC processed images were gathered, whereas table (Tab. 7) shows deviation values of images after orthorectification, used in further parts of urban areas classification research.

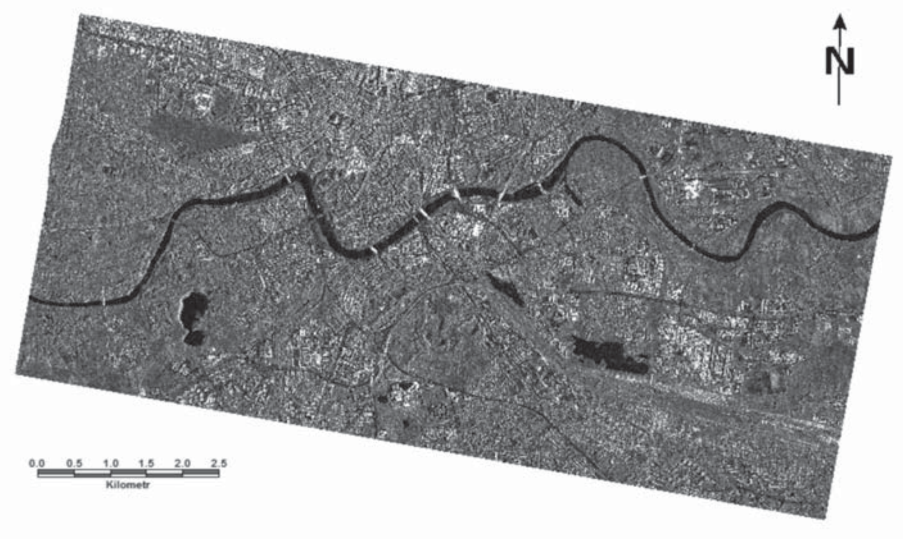

Fig. 5. TSX-1 image check points placement

Table 6. Accuracy analysis of EEC processed images

Scene	RMS_X [m]	RMS_Y [m]	RMS_{XY} [m]
TSX-1	3.58	1.09	3.74
TSX-5	1.90	1.35	2.33
TSX-6	2.52	1.21	2.80

Table 7. Accuracy analysis of orthoimages generated based on SSC data

Scene	RMS_X [m]	RMS_Y [m]	RMS_{XY} [m]
TSX-2	1.82	1.23	2.20
TSX-3	1.78	1.24	2.17
TSX-4	2.32	2.17	3.18

9. Conclusions

Accuracy analysis of performed orthorectification of TerraSAR-X images showed, that using a rigorous Range-Doppler model, selecting 3 to 5 ground control points is an optimal solution. Accuracy levels of orthoimages, generated based on numerical DEM LPIS and DTED-2 models, were very similar, and working with the precise DEM LPIS elevation model improved the accuracy results only slightly. It should be added though, that subject to the analysis was mainly urban area with irregular terrain shape. The analysis of differences on images showed high accuracy of DTED-2 model and little differences in comparison to the DEM LPIS model. The biggest differences of height throughout the city occurred for the Wawel Hill (up to 27 m) and the Liban Quarry (up to 53 m). These two objects do not exist on the DTED-2 model. Whereas as far as buildings areas are concerned, an average difference between them was 0.003 m, with standard deviation of 0.11 m, maximum values did not exceed 2.5 m. High geometrical accuracy of TerraSAR-X products, provided by the producer in EEC format, was confirmed in the study. These images can be used in many aspects, connected with environmental planning and protection, application for map generation and monitoring purposes. However, due to the possibility of data registering regardless of atmospherical conditions or time of day (day or night), data can be particularly useful in critical situations, when registering optical images is impossible. Performed analysis shows, that ordering TerraSAR-X images in complex SSC format has its reason mainly when they are used for radar interferometry and during long-term changes detection. It is significant to notice, that during geometrical correction of radar images basic knowledge on microwave beam scatter mechanisms as well as on possible distortions, different from those that could be observed in case of optical images, is essential. Additionally, complex data processing means obtaining specialistic software.

References

[1] Huang G.M., Guo J.K., Lv J.G., Xiao Z., Zhao Z., Qiu C.P.: *Algorithms and experiment on SAR image orthorectification based on polynomial rectification and height displacement correction*. Proceedings of Geo-Imagery Bridging Continents, XXth ISPRS Congress, Istanbul 2004.

[2] Loew A., Mauser W.: *Generation of geometrically and radiometrically terrain corrected SAR image products*. Remote Sensing of Environment, vol. 106, 2007, pp. 337–349.

[3] Nonaka T., Ishizuka Y., Yamane N., Shibayama T., Takagishi S., Sasagawa T.: *Evaluation of the geometric accuracy of TerraSAR-X*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XXXVII, part B7, Commission VII, ISPRS Congress Beijing 2008, pp. 135–140.

[4] Roth A., Huber M., Kosmann D.: *Geocoding of TerraSAR-X data*. Proceedings of Geo-Imagery Bridging Continents, XXth ISPRS Congress, Istanbul 2004.

[5] Schmidt N., Weber M., Raggam J., Gutjahr K., Wimmer A.: *TerraSAR-X value added image products*. W: Stilla U. (Ed.), Mayer H., Rottensteiner F., Heipke C., Hinz S., *PIA07 – Photogrammetric Image Analysis*, The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. 36, part 3/W49A, 2007.

[6] Schwarz G., Espinoza Molina D., Breit H., Datcu M.: *Adapting multilooking for joint radiometrical and geometrical SAR image enhancement*. ESA – EUSC Conference, Frascati 2008.

[7] Small D., Schubert A., Rosich B., Meier E.: *Geometric and radiometric correction of ESA SAR products*. Proceedings of ENVISAT Symposium 2007, Montreux (Switzerland) 2007.

[8] *TX-GS-DD-3302. TerraSAR-X. Ground Segment. Basic Product Specification Document*. Issue 1.6. 18.03.2009.