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Geometrical Capacity of the VHRS Images Collected with Significant Off Nadir Angle

Wiesław Wolniewicz
Koszalin University of Technology

1. Introduction

All the systems of satellite imaging of the very high resolution (VHRS) have an option of deflecting the optical system from vertical line in all directions by substantial deflection angles. This capacity greatly facilitates the planning of imaging interesting areas in a given traces of satellite. It involves, however, an increase of the angle of camera deflection what results in deteriorated image resolution and increased influence of de-leveling, thus making the process of elaboration even more difficult. For this reason, one uses for mapping the images obtained with the minor angle of camera deflection, which does not transgress 15° – 20°. This paper analyzes the effects of greater deflection and presents the results of geometrical adjustment for Ikonos images off nadir 43°. The results obtained are very promising and encourage to broader application of such images.

2. Specifics Of Geometry Of The Very High Resolution Satellite Images (VHRS)

We tend to perceive geometry of satellite cameras as the kind of the well-known geometry of the aerial photo-grammetrical cameras. However, we should bear in mind substantial differences between them that result in an opportunity for completely different and new approach to geometry of satellite images, especially the ones of the very high resolution.

1. Satellite scanners, especially the ones of the very high resolution, can be characterized by a very small angle of view. It results, first of all, from the very big focal length of optical system (for instance, in Ikonos system, the

telescope has its focal distance of 10 meters, with the angle of view 0.95°, which for the QuickBird system is respectively 2.10°).

2. Internal geometry is very well defined (the camera is calibrated), and the parameters of calibration are stable in time (stability of space conditions).
3. Elements of external orientation of the images are measured on an ongoing basis, with great frequency and accuracy. Location, with accuracy of meters, is measured with a use of GPS, and the elements of angle orientation are measured with accuracy of arc seconds by inertial system (INS). Systematic error of inertial system (drift) is adjusted by the star tracker.
4. Imaging is produced on an ongoing basis, and we deal with the dynamic recording here.

All the above-mentioned results in an option for localization (geo-reference) of the objects subject to imaging only on the basis of the satellite data (so without the points of ground control) with accuracy of several to dozens of meters.

Analysis of residual errors of such image shows its definitely systematic and linear character (distortion vectors have more or less the same length and direction). This systematic results from very strong correlation of elements of external orientation: longitudinal deflection of optical system correlates with positional error in direction of flight, while the transverse deflection correlates with the positional error in lateral direction. Influence of the positional error in direction of length (Z) as well as rotation (κ) is minimal and negligible. In the case of long strips of imaging (more than 50 km), it may be recommended to have an additional parameter describing the drift (alteration) of elements in both directions. Such character of satellite images distortion results from the very narrow angle of view of the camera. Moreover, it causes that the geometry of image is in its first approximation close to parallel projection. In result of the above-mentioned relations between the elements of orientation, it is difficult (practically impossible) to determine precisely, which element is responsible for a given distortion.

The above-mentioned observations prove that classical approach to image geometry and its calibration does not work in the case of satellite images.

The said correlation in influence of the elements of the satellite image orientation and effective – systematic – distribution of residual distortions lead to very important observation from the point of view of practice: in order to ensure correlation of residual errors of such character, i.e. two components of displacement: longitudinal and transverse, it is enough to have a single ground control point on the image. It has been proved in practice; also the results obtained in research of VHRS images conducted by the Institute of Photogrammetry and Carthography from the Warsaw University of Technology have proved the same.

Mathematical model that describes adequately and effectively geometry of the VHRS images of the said specifics is the RPC (Rational Polynomial Coefficient) model. This model has become very popular, and it has become the basic model used for description of the VHRS images geometry. It may also be universal for other images of the very narrow angle of view and of known parameters of external orientation elements. This model defines relations between image coordinates (x_i, y_i) in the focal system and ground coordinates (X, Y, Z) by polynomial coefficients:

$$x_i = \frac{a_1 + a_2X + a_3Y + a_4Z}{b_1 + b_2X + b_3Y + b_4Z}$$

$$y_i = \frac{c_1 + c_2X + c_3Y + c_4Z}{d_1 + d_2X + d_3Y + d_4Z} \tag{1}$$

The model presented is based on the polynomial of the 1st degree. Higher degrees of polynomial may describe additional distortions (optical distortion, refraction, etc.). In the case of VHRS images it is enough to have the polynomial of the 1st degree. Coefficients a_i, b_i, c_i, d_i do not have simple geometrical interpretation, hence RPC model is said to be the non-parametrical one. Distributors of VHRS images define (calculate) these coefficients on the basis of the measured orientation parameters and known elements of the camera internal orientation. These coefficients are enclosed to the supplied images, thus enabling for their further elaboration, like ortho-rectification.

2.1 Influence of the camera deflection upon spatial resolution and imaging efficiency

Angle of view of the camera optical system is fixed. Also, the angles of view of individual pixels of CCD line are fixed. Deflection of the optical system from nadir position results in a change of trace of these angles on the ground area, so they change the dimensions of the ground pixels as well as the width of the imaging area. It has been illustrated on Figure 1.

Deflection angle for the optical system of the very high resolution satellite systems (VHRS) may be very substantial, while the value of the angle of view of the optical system is rather small (some 1°).

This means that in the event of greater deflection of the optical system, the spatial resolution capacity is greatly deteriorated (so the ground size of pixels increases), and also the width of the area subject to images enhances. However, within the imaged scene, due to very narrow angle of view of the optical system, the sizes of pixels – in the first approximation – remain stable and unchanged (provided we neglect the influence of de-leveling).

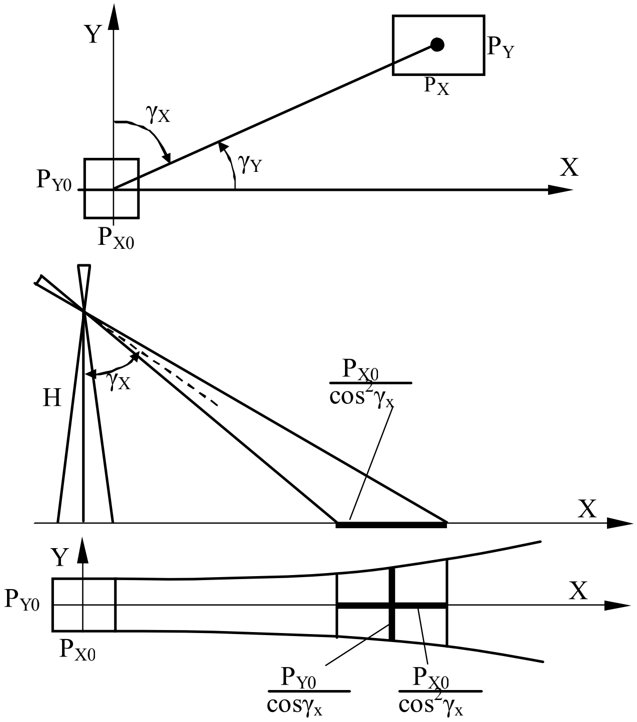

Fig. 1. Influence of the angle of optical system deflection upon the land size of pixel of image and on the width of the imaged strip

Rys. 1. Wpływ kąta wychylenia system optycznego na rozmiar obszaru obejmowanego przez piksel obrazu oraz szerokość fotografowanego pasa

From simple geometrical relations, pursuant to figure 1, one can define the relations between the ground size of pixel in nadir location of camera axis, and its size in the event the camera is deflected.

$$P_X = \frac{P_{X0}}{\cos^2\gamma_X \cos\gamma_Y} \tag{2}$$

$$P_Y = \frac{P_{Y0}}{\cos\gamma_X \cos^2\gamma_Y} \tag{3}$$

where:

P_X – size of the ground pixel in X direction (i.e. crosswise trajectory track),
P_Y – size of the ground pixel in Y direction (i.e. along trajectory track),
P_{X0}, P_{Y0} – sizes of the ground pixel in the nadir location of optical system, respectively in direction of X and Y,
γ_X – deflection of the optical system towards X,
γ_Y – deflection of the optical system towards Y.

Respectively, the width of the imaged area will be:

$$L_X = \frac{L_{X0}}{\cos^2\gamma_X} \tag{4}$$

where:

L_X – width of the imaged area with the optical system deflected crosswise by angle γ_X,
L_{X0} – width of the imaged area with the nadir location of optical system.

The following table illustrates the influence of the deflection angle of optical system upon the size of ground pixel and upon the width of the imaging area, respectively in the systems Ikonos and QuickBird. Figure 2 illustrates the ground size of pixel in relation to the angle of deflection of the optical system.

One should note that the deflection of optical system, despite accompanying deterioration of its spatial resolution capacity, has big importance: increasing the angle of deflection we increase at the same time the width of zone potentially available for imaging. This means that as a result the duration of revisiting is shortened, so the duration of time when a given area may be imaged, and it also enables more flexible programming of the imaged areas, taking into consideration the zones free from clouds during a given run of the satellite. It is directly connected with the imaging efficiency. The width of zone available for imaging – assuming that the acceptable angle of camera deflection is given – depends on the trajectory: the higher the trajectory, the wider the zone is. Wider zone means shortened time of revisiting, thus increasing the chance for imaging a given area within specified period of time. Table 1 presents how this parameter is different for both system, in favor of Ikonos system due to its considerably higher trajectory. Moreover, higher trajectory results in the fact that during the current run of the satellite, with a given maximum angle of camera deflection, the specified area of interest remains within its range for longer period of time. So, in such time it is possible to cover given area with several strips of images with minor overlapped imaging, or to cover it with stereoscope imaging. In practice, it is very important for efficiency of imaging of larger areas. More fundamental analysis shows that in such cases efficiency of imaging depends rather on the height of trajectory than on the width of a single stripof imaging.

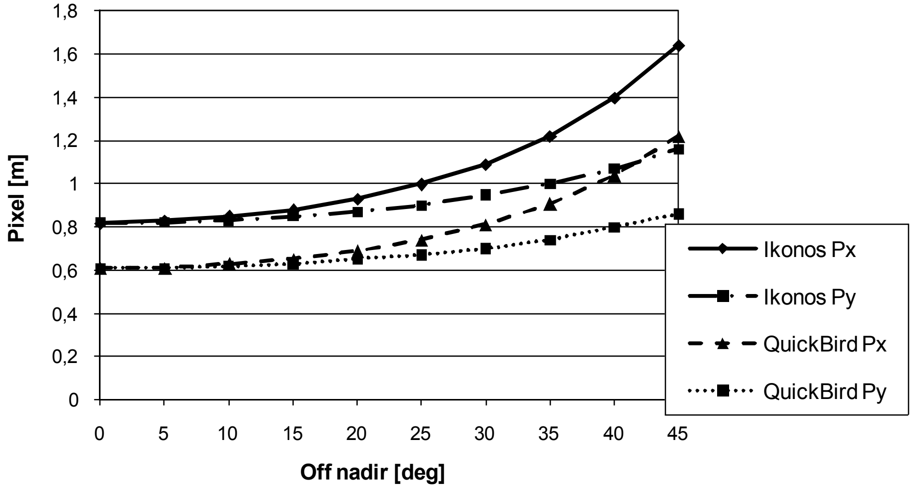

Fig. 2. Terrain size of pixel in function of the camera deflection angle for the systems IKONOS and QuickBird

Rys. 2. Obszar obejmowany przez piksel w funkcji kąta wychylenia kamery dla systemów IKONOS and QuickBird

2.2 Influence of the type of relief on geometry of the VHRS images

Before the very high resolution images have come into existence, with cartographic use of satellite images of medium resolution (for instance: Landsat, SPOT, IRS, and others), the problem of influence of de-leveling upon their geometry was not important. It was due to the following factors:

- Imaging with the vertical orientation of camera what greatly eliminated an influence of de-leveling;
- Relatively low resolution capacity and adequately reduced need for adjustment of errors caused by de-leveling;
- Images of medium resolution have been used mainly for interpretation applications, illustrated by topographical maps, where the problem of cartometry of these products is unimportant.

This situation has rapidly changed ever since the VHRS images emerged. These images enable for manufacture of cartographic products of the very high measurement values, reflecting the medium scales (equivalent of scale 1:10 000, and even higher). On the other hand, optical systems of VHRS may be deflected with considerably larger angles in all directions, what greatly increases flexibility of imaging process and frequency of revisiting, but what also strengthens an influence of de-leveling upon the images obtained. The above-mentioned circumstances cause that de-leveling of terrain constitutes the very primary cause of image distortion what has to be taken into consideration.

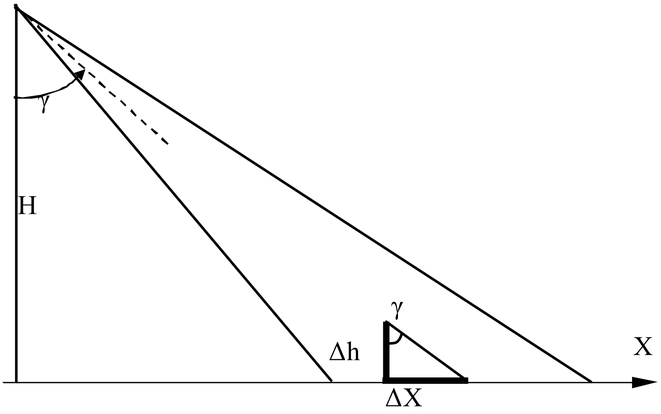

Fig. 3. Influence of de-leveling upon positioning on the image
Rys. 3. Wpływ deniwelacji na pozycjonowanie obrazu

Influence of de-leveling upon image is illustrated in Figure 3. If we skip the Earth curvature, the points of image are radially moved in direction from nadir point by:

$$\Delta X = \Delta h \, tg \gamma \tag{5}$$

where:

ΔX – value of radial move caused by de-leveling;
Δh – value of de-leveling in relation to adopted reference level;
γ – deflection of optical system from vertical line.

The problem of influence of the ground relief is extremely painful in the case of generation of ortho-photo-maps – the most popular product obtained from the VHRS images. The digital terrain model (DTM) is needed for ortho-rectification of images. The above mentioned analyses and conclusions resulting from Figure 4 enable for prognosis of expected accuracy of ortho-rectification of image of known optical system deflection, realized on the basis of DTM of known height accuracy, or vice-versa – to define necessary accuracy of DTM and maximum deflection angle for obtaining the desired ortho-rectification accuracy.

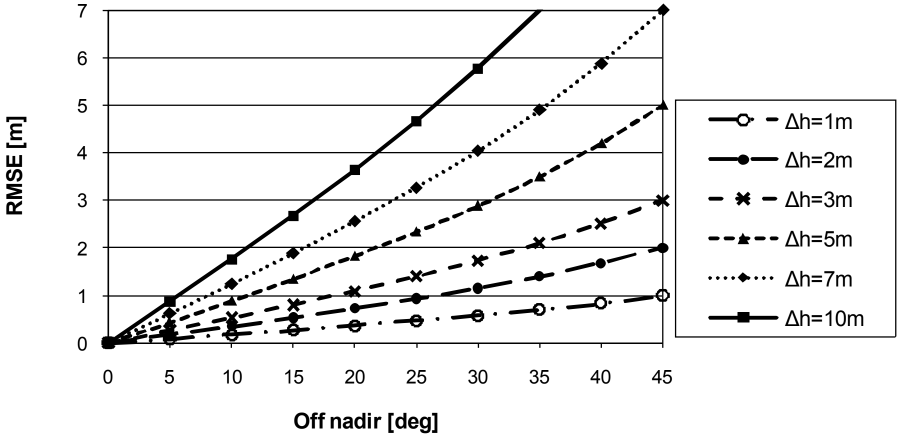

Fig. 4. Quantitative influence of de-leveling in function of the optical system deflection angle

Rys. 4. Ilościowy wpływ deniwelacji w funkcji kąta wychylenia systemu optycznego

For example, if we accept the ortho-rectification error caused by DTM errors to be m_H=1,5 m, then:

- with deflection of γ=10°, the mean DTM error must be $m_H < 8$ m,
- with deflection of γ=15°, the mean DTM error must be $m_H < 6$ m,
- with deflection of γ=20°, the mean DTM error must be $m_H < 4$ m,
- with deflection of γ=25°, the mean DTM error must be $m_H < 3$ m,
- with deflection of γ=30°, the mean DTM error must be $m_H < 2.5$ m,
- with deflection of γ=40°, the mean DTM error must be $m_H < 1.5$m.

Assuming the above-mentioned ortho-rectification accuracy, we may evaluate suitability of available DTM for ortho-rectification of the VHRS images. So:

- DTM DTED Level 2, covering the entire area of Poland, of height accuracy in open flat and corrugated areas being m_H=3 m, is sufficient for ortho-rectification of images of deflection angle up to γ =25°,

- DTM obtained from SRTM radar interferometry data, which covers almost an entire globe, and which is available in Internet in GRID structure GRID of eye 3″ x 3″ (some 90 m x 90 m), of height accuracy some $m_H = 5$ m, is sufficient for ortho-rectification of images of deflection angle up to $\gamma = 15°$,
- DTM of height accuracy $m_H = 1$ m, covering the selected areas of Poland, is sufficient for ortho-rectification of images of any deflection of optical system.

In the event of lesser expectations as to the ortho-rectification accuracy, the requirements for precision of DTM are also weaker, and the acceptable angles of camera deflection are greater, and vice-versa – for manufacture of more precise products, these parameters are respectively more demanding.

3. Experiment

The scenes recorded by the systems IKONOS for different time slots and angle deflections were used for the survey. For flat area (Warsaw) the deflection from axis in relation to nadir point are 10.5 degrees one sine and 43 degrees to another (SCOR provided a test image acquired over Warsaw, Poland). Precise characteristics of the imaging used have been presented in Table 1.

Table 1. Characteristics of imaging used
Tabela 1. Charakterystyka użytego obrazowania

IKONOS data		
Date of acquisition	29-04-2003	12-01-2005
Time of acquisition	09:55	10:25
Off nadir angle [º]	10.59	43.07
Type of data	PAN	PAN
Place of acquisition	EUSI	SCOR
Radiometric resolution	11 bit	11 bit
Field resolution [m]	0.85x0.84	1.48x1.09
Scene size [km]	21x11	17x21

Fig. 5a. Warsaw from IKONOS with off nadir 10.5 degree
Rys. 5a. Warszawa z IKONS'a, kąt wychylenia 10,5 stopni

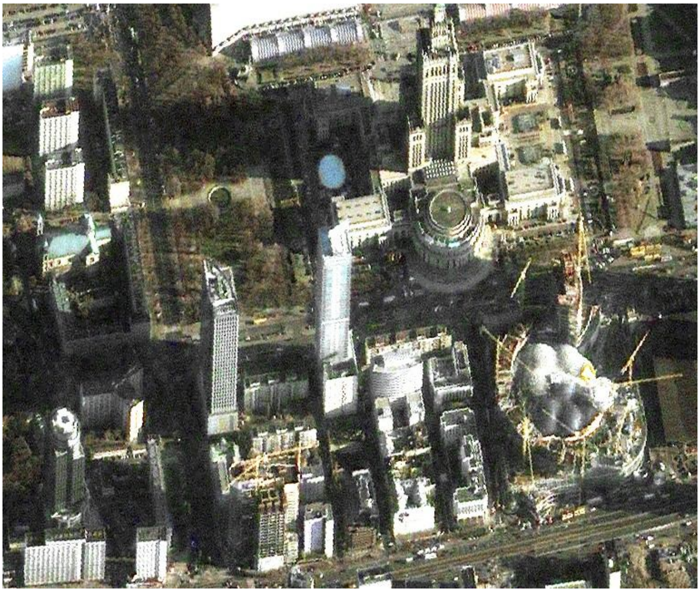

Fig. 5b. Warsaw from IKONOS with off nadir 43 degree
Rys. 5b. Warszawa z IKONS'a, kąt wychylenia 43 stopnie

In order to perform the process of ortho-rectification, we presumed a photogrammetry matrix with the use of a GPS system. For determining coordinates of these points a TRIMBLE 4700 satellite dual-frequency receiver with Micro-centere antenna was used. The survey was done with a use of the fastatic method with an accuracy 0.1 m in the terrain for the values of x, y and z. During the survey, the terrain points were documented with photographs, on which the terrain situation and survey position were visible. They were used together with photographic sketches for pointing out the characteristic points on images

The process of determining coordinates future points to be used for correlation and for controlling mapping quality of the achieved points constituted a very important element. In each case we tried to ensure that the accuracy of GCP identification on the imagery was definitely below one pixel.

Thanks to using GPS receiver for collections the GCP points, all coordinates are of exactly the same accuracy of measurement, which considerably affects the result of adjustment. For ortho-rectification we used one types of DTM: Digital Terrain Elevation DATA-Level 2 like accuracy type of grid 1x2" and height accuracy 1-2 meters for this area.

3.1. Processing

Ortho-rectification process was conducted using commercially available software: PCI Geomatica 9 including a module Ortho-Engine. This software enables the use of several methods of geometrical adjustment. In the framework of tests two methods were used:

Rational polynomial coefficient (RPC) method is the 3D model describing the relation's land-image in form of polynomial quotient. "Firmware information" of mathematical relations in form of RPC coefficients is transferred within the image ordered. Terms of polynomial have no simple physical or geometrical interpretation connected with the parameters of camera of the image distortion factors; therefore it is called the "non-parametrical" model. These models take into account DEM height values for imaging terrain, and to a great extent they are free from the common disadvantages of polynomial coefficient transformations.

The parametrical model (PM) describes actual relations between the land and its image, therefore the terms of this model have a precise geometrical interpretation. The basis for construction of the precise model for satellite imaging is the condition of co-linearity. In this point, however, it may be applied not to the entire image, but only to a single line. Parametrical models are less susceptible to photo-points distribution and possible errors in data. In the framework of research we used PCI software, taking into consideration the approach of Touitn on parametrical relations for VHR type images. In the framework of survey conducted we presumed that the orthophotomap generated would be created in the "1992" Projection Gauss-Kruger; Spheroid: GRS80; Datum ETRS89 system, hence all auxiliary data for this process, namely GCP and DEM, had been previously transformed for this system. We also presumed that for accurate analysis of orthophotomaps created, only the VHRS images in panchromatic range were used.

3.2. Results and analysis

We required orthophotomaps for IKONOS images with a use of the parametrical method (PM) (with use of a camera model) and the Rational Polynomial Coefficient (RPC) method, based upon PCI software. Uniform distribution of adjustment points for both methods was presumed. Figures 6-7 present a specification of required accuracy of generated orthophoto-process. Each figure presents the achieved accuracy of ortho-rectification for a given sensor and type of terrain depending on a number of GCP points. Achieved accuracy was checked on controlling points, which did not take part in the process of ortho-rectification. In the framework of each scene we checked upon the accuracy achieved on controlling points (ICP) in number of some 10-20.

Table 2. Comparison of RMS and maximum errors over 15 ICPs of parametric model and RPC computation with 10 GCPs
Tabela 2. Porównanie RMS i błędów maksymalnych dla 15 punktów kontrolnych modelu parametrycznego i obliczeń RCP z dziesięcioma GCP

	RMS (m)		Maximum (m)	
Off nadir	X	Y	X	Y
43 deg	2.06	1.94	2.77	2.92
10.5 deg	1.09	1.02	2.00	2.11

Table 3. Comparison of RMS and maximum errors over 15 ICPs of parametric model and RPC computation with 10 GCPs
Tabela 2. Porównanie RMS i błędów maksymalnych dla 15 punktów kontrolnych modelu parametrycznego i obliczeń RCP z dziesięcioma GCP

	RMS (m)		Maximum (m)	
Off nadir	X	Y	X	Y
43 deg	1.86	1.64	2.77	3.02
10.5 deg	1.11	1.09	1.80	1.99

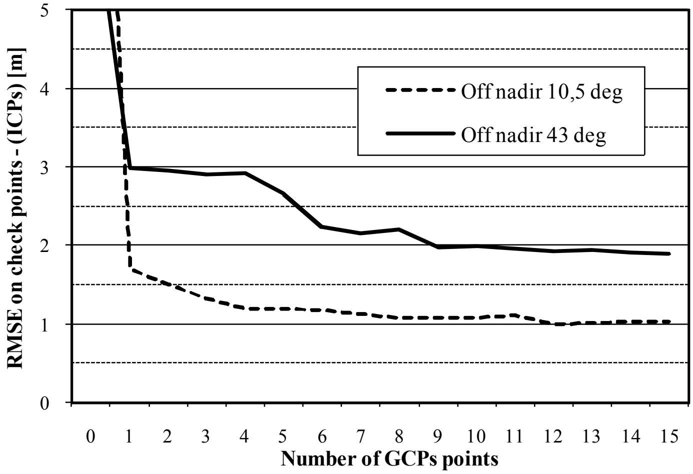

Fig. 6. Accuracy of IKONOS for RPC approach
Rys. 6. Dokładność IKONOS'a dla metody RPC

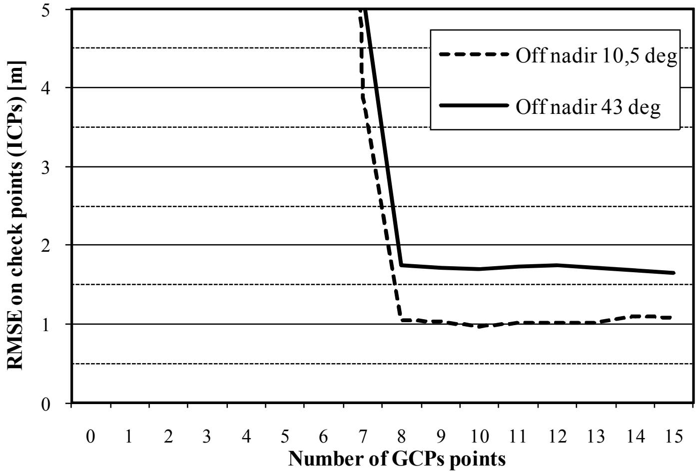

Fig. 7. Accuracy of IKONOS for parametric approach
Rys. 7. Dokładność IKONOS'a dla metody parametrycznej

1. For flat areas (Figure 6), with a use of DEM of accuracy 1-2 meter (Z) and with a use of altimetrical points from GPS survey for IKONOS, method RPC achieved accuracy for image with 10 deg (RMS) of 1.2 meter - with 3 GCP. For the data with 43 deg. we achieve for the same condition RMS like 3 m for GCP used.

2. In case of correction with parametric methods for the same conditions, image with 10 deg gives accuracy (RMS) of 1 meter, but with a 43 deg we can obtain RMS nearly 1.8 meter with 8 GCP (Figure 7).

4. Conclusions

1. VHRS imaging of large deflection angle of camera has practical meaning in:
   - Increasing the space of the imaged zone;
   - Increasing imaging efficiency, in particular for larger areas;
   - Strengthening the chances for obtaining the image within the scheduled period of time.
2. In the case of imaging with the large camera deflection angle, one should consider deterioration of radiometric quality of images, caused by greater influence of the atmosphere (imaging is effected by „thicker” layer of atmosphere than in the case of vertical imaging).
3. Even with the substantial deflection of camera it is still possible to obtain a cartometric product (ortho-photo-map) of geometrical accuracy corresponding with the resolution (pixel dimensions), and with the moderate number of photo-points, and DTM of parameters available for majority of the European states.
4. Obtained practical results confirm earlier theoretical analyses.
5. Obtained results encourage for broader use of VHRS images of large angle of camera deflection. Such images may be used for many different purposes, for instance in agriculture, where the date of obtaining the image may be of critical importance. The results obtained meet the requirements of EU in the field of generation of ortho-photo-maps as the geometrical base for the system LPIS – IACS.
6. The images of large deflection angle have different characteristics as far as the interpretation is concerned what may constitute an advantage for some applications, for instance: the „perspective” view of the city with high buildings and visible building facades may constitute an additional trump for urban and land development experts.
7. Evaluating usefulness of the VHRS images for map applications, one should be aware of two limitations: geometrical accuracy and their contents. The second aspect is far more critical. On the basis of such images, one can produce ortho-photo-maps of parameters corresponding to the scale 1:5 000. However, these images cannot fully meet the requirements for creation of maps with the contents corresponding to traditional topographic map of scale 1:10 000. It follows from the studies performed by the author that the contents of VHRS images correspond to the contents of traditional aerial photographs in scale 1:25 000 – 1:40 000.

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Potencjał pomiarowy obrazów VHRS o dużym kącie wychylenia kamery

Wstęp

Wszystkie systemy obrazowania satelitarnego o bardzo dużej rozdzielczości (VHRS) mają możliwość wychylania układu optycznego od linii pionu we wszystkich kierunkach o znaczne kąty. To znakomicie ułatwia planowanie obrazowania interesujących obszarów w danym przejściu satelity. Jednak wraz ze wzrostem kata wychylenia kamery pogarsza się zdolność rozdzielcza obrazu i rośnie wpływ deniwelacji, co utrudnia proces opracowania. Z tego powodu, dla celów mapowania, wykorzystuje się obrazy pozyskane przy niewielkim kącie wychylenia kamery, nie przekraczającym 15° – 20°.

W artykule przeanalizowano ilościowe skutki większego wychylenia i zaprezentowano wyniki korekcji geometrycznej obrazu IKONOS o wychyleniu 43°. Uzyskane wyniki zachęcają do szerszego stosowania takich obrazów. Mogą one zostać użyte dla wielu innych celów, na przykład w rolnictwie, gdzie data uzyskiwania obrazu może mieć krytycznego znaczenia. Uzyskane wyniki spełniają wymagania UE w dziedzinie tworzenia orto-foto-map jako geometryczna podstawa dla systemów LPIS - IACS.

Obrazy uzyskane pod dużym kątem wychylenia mają inną charakterystykę jeśli chodzi o interpretację co może być zaletą dla niektórych zastosowań, na przykład „perspektywiczny” widok miasta z wysokimi budynkami i widoczne fasady budynków może być dodatkowym atutem dla ekspertów zagospodarowania miasta.

Oceniając przydatność obrazów VHRS do tworzenia map, należy być świadomym dwóch ograniczeń: geometrycznej dokładności i ich zawartości. Drugi aspekt jest o wiele bardziej krytyczny. Na podstawie takich obrazów, można tworzyć orto-foto-mapy o parametrach odpowiadających skali 1:5 000. Jednakże te obrazy nie mogą spełnić wymagań do tworzenia map odpowiadających tradycyjnej mapie topograficznej w skali 1:10 000. Wynika to z badań wykonanych przez autora – zawartość obrazów VHRS odpowiada zawartości tradycyjnych zdjęć lotniczych w skali 1:25 000 - 1:40 000.