DOI 10.1515/gein-2015-0001 GEOINFORMATICA POLONICA
14: 2015

Katarzyna Osińska-Skotak[1], Rafał Zapłata[2]

ANALYSIS OF USEFULNESS OF SATELLITE IMAGE PROCESSING METHODS FOR INVESTIGATIONS OF CULTURAL HERITAGE RESOURCES

[1] Warsaw University of Technology, Faculty of Geodesy and Cartography,
Department of Photogrammetry, Remote Sensing and Spatial Information Systems
pl. Politechniki 1, 00-661 Warszawa
k.osinska-skotak@gik.pw.edu.pl

[2] Cardinal Stefan Wyszyński University in Warsaw, Faculty of History and Social Sciences,
Institute of History of Art, Department of Conservation of Monuments
ul. Wóycickiego 1/3, bud. 23, 01-938 Warszawa
rafalzaplata@poczta.onet.pl

Key words: cultural heritage, remote sensing, WorldView-2

Abstract

The paper presents the analysis of usefulness of WorldView-2 satellite image processing, which enhance information concerning the cultural heritage objects. WorldView-2 images are characterised by the very high spatial resolution and high spectral resolution; that is why they create new possibilities for many applications, including investigations of the cultural heritage. The vicinities of Iłża have been selected as the test site for presented investigations. The presented results of works are the effect of research works, which were performed in the frames of the scientific project "Utilisation of laser scanning and remote sensing in protection, investigations and inventory of the cultural heritage. Development of non-invasive, digital methods of documenting and recognising the architectural and archaeological heritage", as the part of "The National Programme for the Development of Humanities" of the Minister of Science and Higher Education in the period of 2012–2015.

ANALIZA PRZYDATNOŚCI METOD PRZETWARZANIA OBRAZÓW SATELITARNYCH W BADANIACH ZASOBÓW DZIEDZICTWA KULTUROWEGO

Słowa kluczowe: dziedzictwo kulturowe, teledetekcja, WorldView-2

Abstrakt

W artykule przedstawiono analizę przydatności przetworzeń obrazów satelitarnych WorldView-2 uwypuklających informacje na temat występowania obiektów dziedzictwa kulturowego. Obrazy WorldView-2 charakteryzują się bardzo wysoką rozdzielczością przestrzenną i dużą rozdzielczością spektralną, dzięki czemu stwarzają nowe możliwości w wielu zastosowaniach, w tym także w badaniach zasobów dziedzictwa kulturowego. Obszarem testowym dla prezentowanych badań są okolice Iłży. Przedstawiane rezultaty prac są wynikiem zadań badawczych realizowanych w ramach projektu naukowego pt. „Zastosowanie skaningu laserowego oraz teledetekcji w ochronie, badaniu i inwentaryzacji dziedzictwa kulturowego. Opracowanie nieinwazyjnych, cyfrowych metod dokumentacji i rozpoznawania zasobów dziedzictwa architektonicznego i archeologicznego" w ramach programu Ministra Nauki i Szkolnictwa Wyższego pod nazwą „Narodowy Program Rozwoju Humanistyki" w latach 2012–2015.

1. INTRODUCTION – REMOTE SENSING IN ARCHAEOLOGY

Aerial photographs have been applied in archaeology for many years. Their potential values for documenting, inventory and searching for the cultural heritage resources is well known and applied in practice. Due to the lower spatial resolution, satellite images were relatively seldom applied in research works concerning the cultural heritage resources. However, their application in archaeology has been growing together with the development of satellite technologies. This results from the growing spatial and spectral resolution of satellite images of the new generation and from the wider access to portals containing satellite images.

Specially processed aerial photographs and satellite images allow the scientists to investigate relics of human activities from the past, to analyse relations between the past social-and-cultural phenomena and to search for new archaeological sites. This concerns, in particular, the analyses of structures of settlement and places connected with past economic activities, where satellite images gradually become the valuable tool allowing for recognition of the cultural heritage.

Remote sensing techniques have been known and applied in archaeology since the beginning of the 20th century, however, they have been mainly focused on utilisation of aerial photographs. As early as in the second decade of the 20th century box kites were applied for documenting archaeological excavation works, and aerial photographs were considered for documenting monuments in the Middle East (Rączkowski, 2002). The next and important stage of the development of the discussed method was connected with works of O. G. S. Crawford, who is known as "the father of aerial archaeology"; he directed successive development of aerial archaeology (Rączkowski, 2002). In 1979, using aerial photographs, the antique Roman villa (*Gallo-Roman villa rustica)* was discovered in Burgundy, France (http://www.informatics.org/france/romanvilla.jpg). The aerial photographs, taken just after the rainfall, enhanced the clear outline of the antgique villa (Orlando and Villa, 2011). Another example may be the discovery of Roman settlements in England, dated for 48 year of the new era. They were discovered as a result of analysis of differences in textures and tones of arable fields, presented in aerial photographs (Poter and Robinson, 2000). In the Great Britain many objects of the cultural heritage has been still discovered using aerial photographs. They are mainly the relics of objects of religious practices, tombstones, oval barrows and cemeteries from the bronze epoch and the Roman period (Common work, 2011).

The recent and spectacular event, which took place in Poland, was connected with discovery of the first location of the city of Szamotuły by W. Rączkowski from Adam Mickiewicz University in Poznań (Pietrzak, Rączkowski, 2006). Aerial photographs taken in July presented the spatial system of the medieval city in the field of maturing crops. It was very difficult to notice this spatial system on photographs taken in another time, e.g. in June.

Numerous examples of utilisation of aerial photographs and satellite images in archaeology concern archaeological research of tropical forests in Amazonia and in deserts, i.e. in hardly accessible areas, which were slightly modified by contemporary humans. They are the areas where remote sensing techniques may prove to be very useful for archaeology. In 1980 a group of researchers interested in the history of the ancient city of Iram – a fabulous city mentioned in *One Thousand and One Night Stories* – discovered a place where this city is located, using satellite data available from NASA, radar data, SPOT satellite images and images acquired during the Challenger space shuttle mission. Iram of thousand pillars is the lost city in Ar-Rab al-Chali desert, located in contemporary Oman. The city existed since the 3rd millennium B.C. to the beginnings of the new era. It was well known because of palaces and churches of gold-plated columns. According to Koran, Iram was destroyed since these inhabitants, who were dealing with occultism and praying to rock idols, did not convert themselves (Groom, 1981).

In 1984 Payson Sheets, the archaeologist from the Colorado University, was investigated prehistoric villages in tropical forests in Costa Rica. This area was destroyed by 10 volcanic eruptions within the period of 4000 years, but villages were restored, covered by ashes. In order to investigate this area remote sensing techniques were widely applied – it was one of the biggest experiments in this field. Within two years the team of T.L. Sever performed a series of flights and acquired satellite images. Among others aerial photographs in natural colours and infrared photographs, as well as thermal data from TIMS scanner, radar data acquired in two channels and LANDSAT satellite images, were acquired (Sever T.L., 1998a). Infrared photographs present linear elements which were initially considered as roads. Later, basing on archaeological excavations, the presence of hardened route for pedestrians sacbé, was determined, which connected particular political and ritual centres of the ancient civilisation of the Mayans. Some routes were visible on thermal images only, since they were covered by dense crowns of trees. The oldest routes are dated as about 500 years BC. T.L. Sever and his team utilised many diversified sources of remote sensing data for the needs of investigating the Mayans' civilisation. Within the area of Petén, in northern Guatemala, they utilised such data for mapping connections between particular religious-and-political centres. Artefacts which existed in the landscape and which were visible on satellite images were used for identification of such objects. SAR radar data was used for mapping the networks of channels and water melioration systems. Using satellite images, the members of T.L. Sever's team were able to estimate the development of the Mayans' civilisation in various periods. They estimated that the density of population in rural areas, located in lowlands, equalled between 500 and 1300 individuals per sq. kilometre; it was even higher in urban centres. As it turns out from various data, rainforests were highly debased at the end of the classic era. Wide investigations concerning the Mayans' civilisation and their rapid fall have lead T.L. Sever to the statement that the probable reason of the fall of the Mayans' civilisation was the ecological disaster. He also supposes that the currently performed loggings of tropical forests may lead to the similar situation on the future and, therefore, that investigations of the past may contribute to foresee the future of this region.

From the archaeological perspective thermal remote sensing turned to be interesting. One of the first research works, performed with the use of the TIMS thermal scanner were performed in the eighties of the 20th century in Chaco Canyon, New Mexico. Utilisation of this spectral range it was possible to identify prehistoric roads, walls, buildings and arable lands, covering the area of 200 miles. Those objects were dated of approximately the year 900 of the new era. In this case, testing of grounds, aerial photographs in true colours and in infrared, did not prove anything; it was the TIMS scanner which disclosed the mentioned objects (Sever, 1998b).

Together with disclosing the Russian satellite data it was possible to utilise it for civilian purposes, including archaeological research works. For the needs of such works M.J.F. Fowler (1996) utilised data acquired by the Russian KVR-1000. He applied this data for documentation and analysis of the Stonehenge area. His later works were focused on, among others, comparative analysis of various satellite images used for archaeological analysis; they included LANDSAT, SPOT and KVR-1000 data (Fowler, 2002).

In 1996 satellite images acquired by the American CORONA system were disclosed (http://eros.usgs.gov/#/Find_Data). They turned to be very interesting for many archaeologists (UR, 2003; Challis et al., 2004; Goossenss et al., 2006; Casana et al., 2012). They allowed, among others, for investigations of the network of ancient roads in the northern Mesopotamia (Ur, 2003; Casana et al., 2012). Archive aerial and satellite images are of great value for archaeological research works, since they present particular areas in the more natural conditions, without man-made features, which are currently present in these areas. That is why objects, which are currently present within densely built-up areas, may be located using such images. This may be the reason of high interest, expressed by researchers in CORONA archive satellite images, which are, at the same time, characterised by the high spatial resolution (the pixel size: 2×2 m).

Radar data has also been very interesting for archaeologists from the very beginning. The first SIR-A radar mission, which took place in November 1981, acquired the first – at the regional level – images of subsurface objects, which were not known before, which were located in river valleys in the eastern Sahara, in Egypt and Sudan (Corrie et al., 2011). Aerial STAR3i and IFSAR radar data allowed Saturno et al. (2007) to discover proofs of prehistoric activities within the area of the Homul River in Guatemala, and the team of T.L. Sever applied those images for investigations of the water melioration networks of the Mayans' civilisation.

Although many cultural heritage objects have been already discovered, successive, spectacular discoveries still appear in archaeology. In 2011 Sarah Parcak with her team identified 17 buried pyramids in Egypt, about 3000 ancient settlements and 1000 tombstones using satellite infrared images (ASTER, LANDSAT, QuickBird) (National Geographic[1]; NASA, 2011). She

[1] http://ngm.nationalgeographic.com/2013/02/125-explore/satellite-archaeology

stated that it might turn that only 1% of the ancient Egypt object had been discovered and that thousands of other object existed, which were covered in sludge by the Nile and which were hiding monuments of the ancient culture.

After appearance of the satellite systems of very high spatial resolution, the interest in utilisation of satellite images in archaeology has been constantly increasing (De Laet et al., 2007; Lasaponara and Massini, 2007; Massini et al., 2007; Orlando and Villa, 2011; Saturno et al., 2007). Satellite which register images of the pixel size of several dozens metres allowed for discovery of very big objects of the cultural heritage. Besides, current land use and land cover make utilisation of remote sensing techniques in archaeological research very difficult. In Poland excessive fragmentation of arable lands results in mosaicking of images and in difficulties concerning the discovery of traces from the past. However, traces from the past may be noticed in some seasons. The moment of data acquisition (the season, the time of day) and its geometric features are very important due to the possibility to detect archaeological objects. The above examples also point to the high importance of the data acquisition time in the context of possible observations of the cultural heritage objects.

Very high resolution satellite images created the chance for investigations of smaller surface objects. IKONOS and QuickBird satellite images were applied in investigations of the ancient Mayans' civilisation among others by Saturno et al. (2007). R. Lasaponara and N. Massini (2007) applied QuickBird images for archaeological investigations of medieval objects in southern Italy, where a special image processing scheme has led to discovery of two archaeological sites. They stated in conclusion, that satellite images of very high spatial resolution were very expensive and they required a special processing station. In practice, costs of purchase of satellite images of very high resolution do not allow for fast development of many disciplines of science, but the development of satellite archaeology is growing faster as a result of utilisation of such portals as Google Earth. Many archaeologists (among others Angela Micol of the University of North Carolina, David Kennedy of the University of Western Australia) utilise this source of satellite data and discover new objects of the cultural heritage.

2. DIGITAL IMAGE PROCESSING METHODS IN ARCHAEOLOGY

The, so-called, crop marks, are applied in aerial and satellite archaeology. If, even small relics of the cultural heritage objects occur, which have their own landscape relief (elevation micro-relief), they may be recorded from the aerial level due to the change of the Sun rays incidence angle (the, so-called, shadow marks), snow – frost (frostmarks) or partial flood (watermarks). Besides, changes caused by the occurrence of archaeological objects may be observed in colours, structure or the soil erosion level (soilmarks) or its moisture (moisturemarks) and vegetation diversification of crops (cropmarks) (more discussion, among others, in Żuk, 2005).

In order to strengthen selected features on aerial photographs or on satellite images, i.e. to create marks, which stress underground objects – various spectral bands and various digital image processing methods are applied. The visible spectral range is preferred for investigations of soils and surface features; this means that these spectral bands should strengthen soil marks, shadow or snow marks. Besides, reflection in middle infrared bands is useful in determination of compactness of soils and their moisture. Thus, middle infrared bands are preferred for searching for soil and watermarks. Near infrared and red spectral bands may help in analysing vegetation and the, so-called, cropmarks within areas covered with vegetation (meadows, arable fields, forests), since they are sensitive to conditions of vegetation and the biomass amount. Poor vegetation conditions result in lower intensity of reflection of infrared radiation; this may be the evidence of the presence of underground obstacles, which do not allow for proper development of vegetation. Another spectral band, which is interesting for archaeologists, is the long-wave infrared radiation, i.e. the thermal infrared radiation, which presents diversified temperature of projected objects. This spectral band is often applied in geology, in searching for minerals or in distinguishing geological features. It may be also used for calculation of such parameters as thermal conductivity or the thermal capacity of objects, located within the study area. As it was proved by researchers (Sever, 1998a, 1998b) sometimes the thermal radiation band is the only band which point to the occurrence of anomalies and subsurface contrasts, and then, to the presence of the cultural heritage objects under the earth surface.

As it turns out from the review of accessible literature, many diversified satellite image processing methods are applied to strengthen information concerning the occurrence of the cultural heritage objects. They are, first of all, the basic contrast enhancement functions – the basic feature which allows for discovery of certain anomalies in the image – and colour composites, which strengthen required features (selection of the best combination of spectral bands). Besides, the principal component analysis is widely applied (Corrie, 2011; Alexakis et al., 2012), as well as vegetation indices, (Lasaponara and Massini, 2007; Alexakis et al., 2011, 2012; Agapioua et al., 2012), weighted spectral bands and indicatory images (Saturno et al., 2007), image filtering (Lasaponara and Massini, 2007; Alexakis et al., 2011, 2012) and digital image classification (Fowler M.J.F., 2002; Corrie, 2011; Alexakis et al., 2012) using unsupervised, supervised and object-oriented methods. All these image processing methods were applied for panchromatic, multispectral, as well as *pansharpened* type images, i.e. images, which are the result of integration of multispectral and panchromatic images. Due to diversification, the relics of human activities, as well as the complexity of the cotemporary landscape it is difficult to point to a universal methods of aerial or satellite image processing, which would always present the existence of underground objects from the past. The short review of selected results of research works performed in the world, in the field of utilisation of satellite images for archaeology is the best proof of this statement.

Analysis, which is mostly applied by archaeologists, is photointerpretation of panchromatic, black-and-white infrared images or colour composites, which contrast was enhanced. Indicatory images are less often utilised. Saturno et al. (2007) applied the LANDSAT TM image for their works in Guatemala; for that image they calculated the indicatory TM5/TM4 image. The resultant image strengthened the dark edges of a dam – relics of the Mayans civilisation. In the case of LANDSAT TM and ETM+ images, the index image may be used for identification of soils, which contains ferrous minerals. The TM5/TM7 index strengthens diversification of clay minerals and the indicator TM3/TM1 – soils and rocks, which contain iron oxides. Besides, index images, in the form of the quotient of two spectral bands, limit to the certain extent the variable influence of illumination of objects, which results from diversification in the topography; this eliminates some artefacts, which occur in the image, which may be considered as possible objects of the cultural heritage.

Vegetation indices strengthen information concerning diversification of vegetation, its biomass, occurrence of stresses, such as lack of water, or diseases or pests, and also other limitations which result in slower development of plants. Alexakis et al. (2011, 2012) and Agapioua et al. (2012) used the NDVI index for detection of elliptical megaliths from the neolithic epoch in the central Greece. The presence of relics of walls of ancient cities and other objects has the effect on development of plants growing above them, since the level of vegetation depends on the soil characteristics. If plants grow "on the walls", their growth is weaker than the growth of other plants and if the plants grow in a fosse, they usually grow more intensively. Therefore, vegetation indices may inform about features, which are located under the ground.

Interesting results of research works were obtained by Alexakis et al. (2011, 2012), who applied high pass filters, Sobel diagonal filter (3×3 window) and Laplace filter (3×3 window) with the ASTER satellite image. It proved the existence of elliptical, neolithic objects within the area of Halki. High pass filters, among others, strengthen the edges. Similar filtering was also applied by R. Lasaponara and N. Massini (2007), but they filtered the NDVI image, i.e. the image of the vegetation index. As a result they discovered two new archaeological sites of the medieval period.

The principal component analysis was applied by many researchers (Corrie, 2011; Alexakis et al., 2012); application of various components resulted in various information. The first three components usually contain more than 90% information of the multispectral image, but as it follows from discussions in professional literature, they are not the sources of information about the underground objects. Works performed by Corrie (2011) in the Nile delta proved, that analysis of the fourth principal component (PCA) of the LANDSAT ETM+ satellite image (2σ contrast stretching) is the best for identification of unknown archaeological sites. In the case of the ASTER satellite image, it was the fifth principal component (PC5), applied with the same contrast stretching factor. New, unknown place were visualised in both images as bright, oval spots. Basing on this it may be concluded that various principal components allow for noticing various cultural heritage objects, which

Fig. 1. The study area (source: maps.google.pl)
Ryc. 1. Obszar opracowania (źródło: maps.google.pl).

are located under the ground, depending on the types of data and objects. It is difficult to point to a universal principal component, which would always point to the location of occurrence of the cultural heritage objects.

3. THE STUDY AREA

The study area is located in the southern part of the Mazovia Voivodship, in the Radom district, close to Iłża. It is located between 21°07′ and 21°16′ of the east longitude between 51°00′ and 51°12′ of the north latitude.

The vicinities of Iłża have long and interesting history. The city of Iłża existed as early as the early Middle Ages and until 1789 it was the property of the Kraków bishops. The city was the centre of the bishops' key (administrative unit)of Iłża goods, including 2 cities and 23 villages in 1645 (Bednarczyk, 1996, Lipińska 1987). The bishops were seated in the castle; its ruins may be also visited at present. The history of those areas is closely connected with the most important events from the history of Poland. The city and the castle were destroyed several times; for the first time it happened during the Tatar invasion in 1241, then it happened in 1260 as a result of the successive Tatar invasion, and later the city was destroyed during the Swedish invasion (deluge), during the invasion of George Rakoczy II and during the First World War, the battles between Russians and Germans, which happened in the area of Iłża and Pakosław, and then, during the Second World War.

The vicinities of Iłża are connected with human activities dated as early as the Stone Age, what should be among others connected with the intensive exploitation of natural resources, such as bended and chocolate flint, which occurs within this area. Outcrops of this mineral may be observed in the belt running from the areas located far to the south, outside the area of the Natural-and-Archaeological Reservation "Krzemionki", connected with monumental objects of exploitation of bended flint (Bodzechów Municipality, Ostrowiec District, Świętokrzyskie Vooivodship) – "Krzemionki – flint mine of the neolithic age", listed in the register of monuments of the Świętokrzyskie Voivodship – A1/499/1Aa, to the areal located to the north, close to Orońsko in the Mazovia Voivodship (Cieślak-Kopyt et al., 2004). Younger ages of the history of Iłża lands have also left their traces in the forms of relics of settlements. Characteristic objects of the cultural heritage include monument connected with the intensive development of the Old Poland Industrial District (Staropolski Okręg Przemysłowy) which happened in these areas (Guldon, Kaczor, 1994). Other objects are, among others, traces of military operations, mentioned above, which considerably influenced the development of the historic map of these areas.

4. SATELLITE DATA

Research works were performed using the example of the WorldView-2 satellite images. It is the satellite system of very high spectral resolution, which records eight spectral bands. Analysed images were acquired on August 23, 2011 and on March 25, 2012. The first image was acquired in the panchromatic mode and the second one both, in the panchromatic, as well in the multispectral modes. Both images are characterised by the a several degrees of deflection from nadir. The basic technical specification, which characterises the discussed World-View-2 images, is presented in Table 1.

Table 1. Technical specifications of analysed WorldView-2 satellite images
Tabela 1. Dane techniczne analizowanych zdjęć satelitarnych w WorldView – 2.

General data		
Acquisition date	March 3,2012	August 23,
Acquisition time	09:53:35.4	09:55:10.0
Product	OrthoStandard 2A	OrthoStandard 2A
Acquisition mode	MS, PAN	PAN
Acquisition geometry		
Global incidence	17.8°	17.4°
Viewing angle across the track/ viewing angle along the track	17.8° / –1.4°	12.7° / 12.0°
Sun azimuth	164.40°	163.80°
Sun elevation	40.10°	49.50°

5. ANALYSIS OF USEFULNESS OF DIGITAL WORLDVIEW-2 SATELLITE IMAGE PROCESSING METHODS FOR DETECTION OF CULTURAL HERITAGE OBJECTS USING THE EXAMPLE OF „IŁŻA” STUDY AREA

Performed research works included a series of satellite image digital processing operations; they covered: various contrast stretching methods, creation of colour composites, digital filtering with the use of various filter (high pass, low pass, edge detection and gradient filters), Principal Components Analysis (PCA), decorrelation of bands, topographic normalisation. All image processing works were performed using the ERDAS Imagine software. The general scheme of research works has been applied during the analyses; it considers verification of results of satellite image analysis basing on: (1) field inspection of selected objects, (2) comparison with archive (cartographic) data, (3) comparison with results of measurements performed using aerial laser scanner data. As a result of tests performed for the Iłża Study Area it turned out that interesting results were obtained using topographic normalisation of images. It allowed for strengthening of certain information, including, among others, the network of old roads, which is presented in figures below. In the process of topographic normalisation the digital terrain relief model is utilised, as well as data concerning the Sun position at the moment of acquisition of the satellite image. Topographic normalisation limits the influence of the terrain relief on tonal variability of the image. The more detailed positions of particular fragments of old roads were delineated as a result of digital filtering of images (high pass and edge detection filters) and calculation of the *iron oxide* index and decorrelation of images. Figure 2 presents the results of selected digital processing operations of the WorldView-2 satellite image acquired on March 25, 2012, which produced the best results for strengthening the tonal variability, connected with existence of relics of the old roads. Vegetation indices, including the NDVI, did not produced satisfactory results in the discussed case.

Basing on analysis of results of digital processing it may be stated that their effects were influenced, among others, on the satellite image acquisition date, on the agricultural structure of the given area and on the land cover types. Figures 3 and 4 presents comparison of the contrast enhancement results (2σ method) of panchromatic images acquired in two different periods. In two areas: the vicinities of Pakosław (Fig. 3) and Krzyżanowice (Fig. 4), where relics of old roads were observed, influences of results of image processing are different.

In the case of Pakosław, outlines of old roads may be observed for both dates, but in the case of Krzyżanowice, relics of old roads are not visible in the satellite image of August 23, 2011. The image of March, 2012 presents clear tonal differences, which suggest the presence of linear objects – roads. An out-

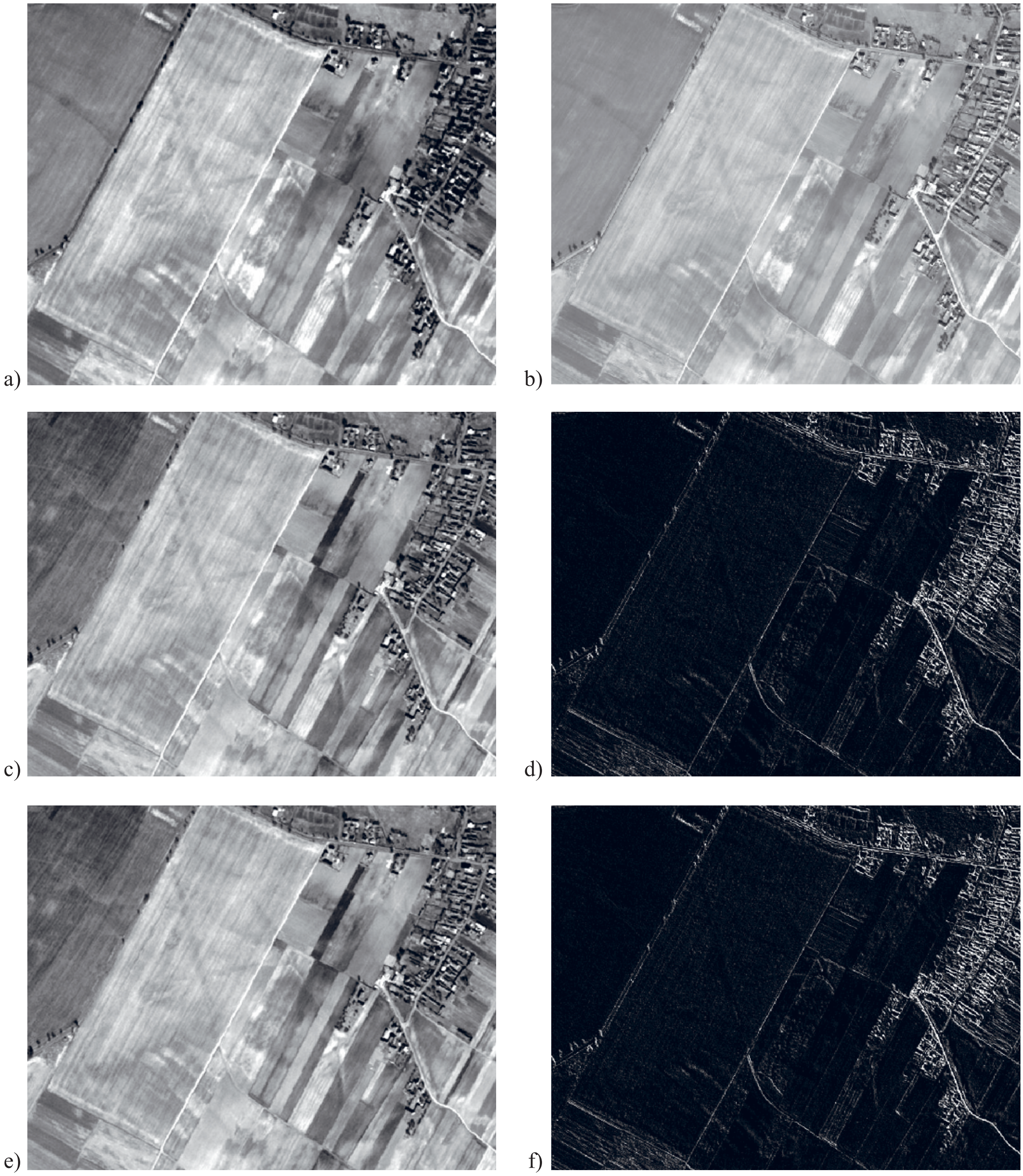

Fig. 2. Comparison of the WorldView-2 panchromatic image processing (the original image was acquired on March 25, 2012). a. the raw image, b. the image after topographic normalisation, c. the *iron oxide* index, d. the image after edge detection filtering (*left diagonal edge detection*) (the filter window 3×3), e. the colour composite after decorrelation, f. the image after edge detection filtering (*right diagonal edge detection*) (the filter window 3×3)

Ryc. 2. Porównanie wyników przetwarzania obrazu panchromatycznego WorldView-2 zarejestrowanego w dniu 25 marca 2012 r. a. obraz źródłowy, b. obraz po normalizacji topograficznej c. wskaźnik *iron oxide*, d. obraz po filtracji filtrem krawędziowym *left diagonal edge detection* (okno filtra 3×3), e. kompozycja barwna po operacji dekorelacji, f. obraz po filtracji filtrem krawędziowym *right diagonal edge detection* (okno filtra 3×3).

a)  b) 

Fig. 3. Influence of the acquisition date on the possibility to interpret cultural heritage objects. Comparison of WorldView-2 panchromatic images of Pakosław, acquired on August 23, 2011 (to the left) and March 25, 2012 (to the right).

Ryc. 3. Wpływ terminu rejestracji na możliwość interpretacji obiektów dziedzictwa kulturowego. Porównanie obrazów panchromatycznych WorldView-2 okolic Pakosławia zarejestrowanych w dniach 23 sierpnia 2011 r. (obraz lewy) i 25 marca 2012 r. (obraz prawy).

a)  b) 

Fig. 4. Influence of the acquisition date on the possibility to interpret cultural heritage objects. Comparison of WorldView-2 panchromatic images of vicinities of Krzyżanowice village acquired on August 23, 2011 (to the left) and March 25, 2012 (to the right)

Ryc. 4. Wpływ terminu rejestracji na możliwość interpretacji obiektów dziedzictwa kulturowego. Porównanie obrazów panchromatycznych WorldView-2 okolic wsi Krzyżanowice zarejestrowanych w dniach 23 sierpnia 2011 r. (obraz lewy) i 25 marca 2012 r. (obraz prawy).

line of a linear object, which is visible in the left part of the image (Fig. 4) is not the old road, but the shadow of a power supply line, what is confirmed by bright spots, which are the electric poles. Such situations often happen, what suggests that photointerpretation and analysis of results of digital image processing should be performed very carefully. Basing on performed analysis it may be stated, that in the case of areas of consolidated agricultural structure (the vicinities of Pakosław), locations of old roads are relatively well visible, independently on the acquisition date. In the case of the area of more diversified agricultural struc-

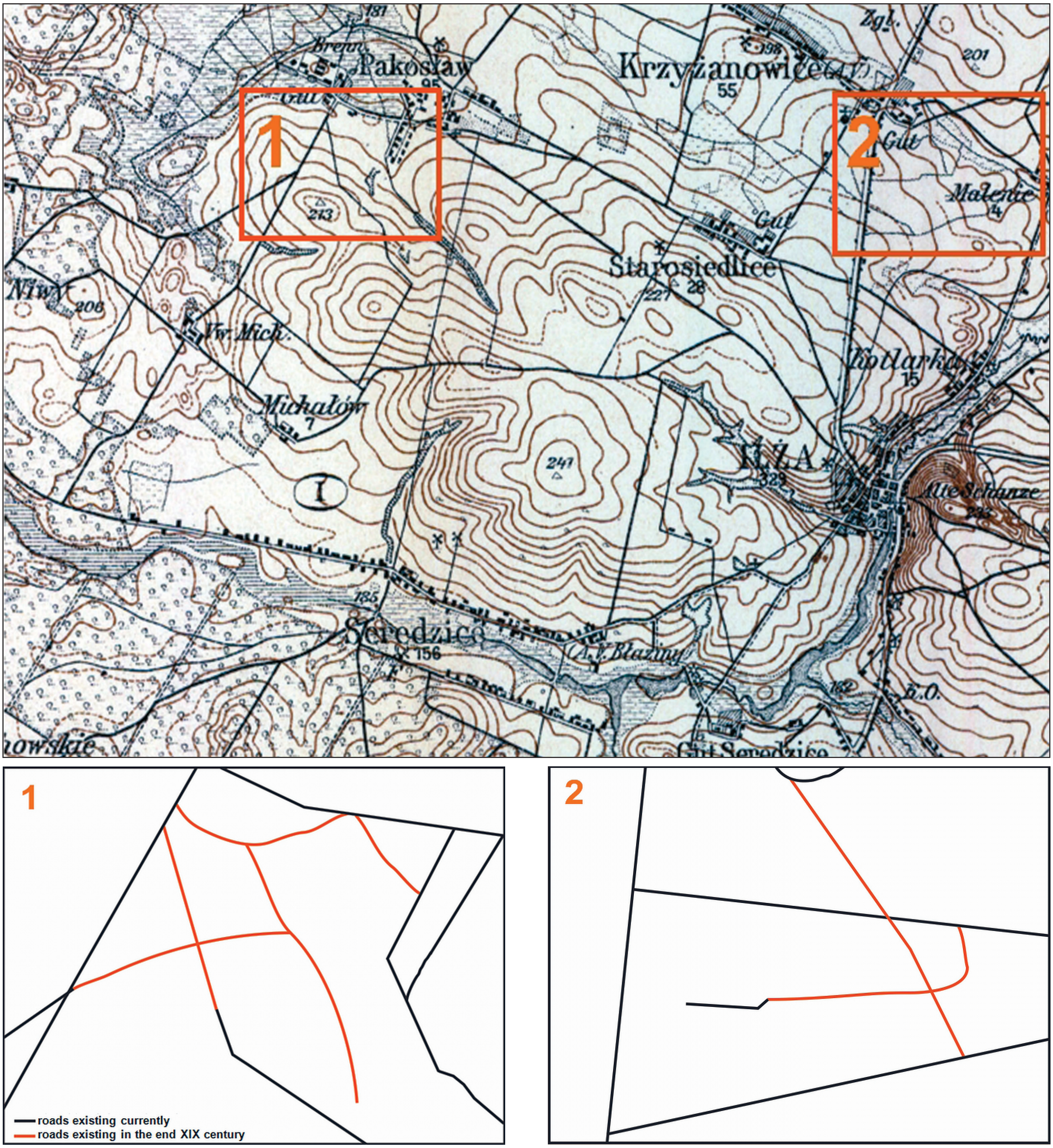

Fig. 5. A part of the „Karte des westlichen Rußlands", at the scale of 1:100 000, based on the Russian maps (1:21 000, 1:42 000, 1:84 000, and in some cases 1:126 000) of the turn of the 19th and 20th centuries, issued in individual map sheets (467 maps) and composite maps [The Map Archives of the Military Geographical Institute, 1919–1939] and the sketch of the road network interpreted basing on the WorldView-2 satellite image

Ryc. 5. Fragment „Karte des westlichen Rußlands", w skali 1:100 000, opartej na mapach rosyjskich (1:21 000, 1:42 000, 1:84 000 i czasem 1:126 000) z przełomu XIX i XX wieku, wydanej w arkuszach indywidualnych (467 map) oraz zbiorczych [Archiwum Map Wojskowego Instytutu Geograficznego 1919–1939] oraz szkic sieci drogowej opracowany na podstawie obrazu satelitarnego WorldView-2.

ture (the vicinities of Krzyżanowice) the influence of the satellite image acquisition date on the possibility to detect relics of the old road network is well visible. The image acquired in August clearly shows areas of agricultural works, which result in high tonal differences of the image, and, therefore, make interpretation of relics from the past more difficult.

Some roads, which are visible in satellite images, may be also found in maps of the turnover of the 19th and 20th century. Figure 5 presents a fragment of the map sheet „H37 – Iłża" of the „Karte des westlichen Rußlands", at the scale of 1:100 000, based on the Russian maps of this time; this map was issued in 1915 by Königlich Preußischen Landesaufnahme (Kartogr. Abteilung des Stellvertretenden Generalstabes der Armee). It presents roads, which then created the road network within this area. Results of vectorisation of traces of old roads proves the compliance with locations of roads, which are visible on the discussed map. Besides roads presented on the map of 1915, roads, which are not visible on this map, were also vectorised (Fig. 5).

Fig. 6. Panchromatic image after topographic normalisation, disclosed the object outline, pointing to potential presence of man-made relics

Ryc. 6. Obraz panchromatyczny poddany normalizacji topograficznej uwidocznił zarys obiektu, który może być obiektem dziedzictwa kulturowego.

Information concerning the road (transportation) network, which existed in the past, is the important resource of data for archaeology and for research works concerning the region history, first of all due to the fact that the past settlement was concentrated along roads, what is also the guideline for interpretation of surrounding objects. Basing on analyses performed along roads and within close surroundings of detected roads, a series of various objects were also detected (such as the object presented in Fig. 6); their verification will be continued in the future.

4. FINAL REMARKS

Performed analyses confirmed, first of all, the usefulness and validity of application of high resolution satellite images for investigations of the cultural heritage – in particular the structures of settlement – within areas, which are characterised at present by intensive agricultural activities, as well as high dispersion of crops. As a result of performed analyses the important influence of topographic normalisation of satellite images on strengthening tonal differences (information) was stated; they pointed to the cultural heritage objects. The *iron oxide* index also proved the high usefulness for these purposes. Both methods of satellite image processing produced information concerning the past location of the road network in the analysed area and pointed to various objects, which might be the cultural heritage objects in this area.

* * *

The research work, financed within "The National Programme for the Development of Humanities" of the Minister of Science and Higher Education in the period 2011–15: the research project „Utilisation of laser scanning and remote sensing for protection, investigations and inventory of the cultural heritage. Development of non-invasive, digital methods of documentation and recognition of architectural and archaeological heritage resources", implemented by the Cardinal Stefan Wyszynski University in Warsaw, in co-operation with the Warsaw University of Technology.

REFERENCES

Agapioua A., Hadjimitsisa D.G., Alexakisa D., Sarris A., 2012. Observatory validation of Neolithic tells ("Magoules") in the Thessalian plain, central Greece, using hyperspectral spectroradiometric data. Journal of Archaeological Science, vol. 39, Issue 5, 1499–1512. http://dx.doi.org/10.1016/j.jas.2012.01.001.

Alexakis D., Sarris A., Astaras T., Albanakis K., 2011. Integrated GIS, remote sensing and geomorphologic approaches for the reconstruction of the landscape habitation of Thessaly during the neolithic period. Journal of Archaeological Science, 38, 89–100.

Alexakis D.D., Agapiou A., Hadjimitsis D.G., Sarris A., 2012. Remote Sensing Applications in Archaeological Research. W: Remote Sensing – Applications, Dr. Boris Escalante (Ed.), ISBN: 978-953-51-0651-7, InTech, http://www.intechopen.com/books/remote-sensing applications/ remote-sensing-applications-in-archaeology

Bednarczyk A., 1996. Iłża wczoraj i dziś. *Iłża yesterday and today.* Wydawnictwo Ararat.

Casana J., Cothren J., Kalayci T., 2012. Swords into Ploughshares: Archaeological Applications of CORONA Satellite Imagery in the Near East. Internet Archaeology. 32. http://dx.doi.org/10.11141/ia.32.2

Challis K., Priestnall G., Gardner A., Henderson J., O'Hara S., 2004. Corona Remotely-Sensed Imagery in Dryland Archaeology: The Islamic City of al-Raqqa, Syria. Journal of Field Archaeology, Vol. 29, No. 1/2 (Spring 2002-Summer 2004), 139–153, http://www.jstor.org/stable/3181489

Cieślak-Kopyt M., I. Micke, E. Skubicha i W. Twardowski 2004. Radomskie. Alfabet wykopalisk, *The alphabet of excavations*, Radom.

Corrie R.K., 2011. Detection of ancient Egyptian archaeological sites using satellite remote sensing and digital image processing. Earth Resources and Environmental Remote Sensing/ GIS Applications II, ed. by Ulrich Michel, Daniel L. Civco, Proc. of SPIE Vol. 8181, doi: 10.1117/12.898230

De Laet V., Paulissen E., Waelkens M., 2007. Methods for the extraction of archaeological features from very high-resolution IKONOS-2 remote sensing imagery, Hisar (southwest Turkey). Journal of Archeol. Sci., 34, 830–841.

Fowler M.J.F., 1996. High-resolution satellite imagery in archaeological application: a Russian satellite photograph of the Stonehenge region. Antiquity, 70, 667–71.

Fowler M.J.F., 2002. Satellite remote sensing and archaeology: a comparative study of satellite imagery of the environs of Figsbury Ring, Wiltshire. Archaeological Prospection, Vol. 9, Issue 2, 55–69.

Goossens R., De Wulf A., Bourgeois J., Gheyle W., Willems T., 2006. Satellite imagery and archaeology: the example of CORONA in the Altai Mountains. Journal of Archaeological Science, Vol. 33, Issue 6, June 2006, 745–755.

Groom N., 1981. Frankincense and Myrrh" A Study of the Arabian Incense Trade, Longman, London.

Guldon Z., Kaczor J., 1994, Górnictwo i hutnictwo w Staropolskim Okręgu Przemysłowym w drugiej połowie XVIII wieku, *Coal mining and metallurgy in the Old Poland Industrial District in the second half of the 18th century.* Kielce.

Lasaponara R., Masini N., 2007. Detection of archaeological crop marks by using satellite QuickBird multispectral imagery. Journal of Archaeological Science, 34, 214–221.

Lipińska O. 1987. Z badań nad wczesnośredniowiecznym osadnictwem północnej części Przedgórza Iłżeckiego, *On investigations of early medieval settlement in the northerns part of Iłża Foreland*, [w:] Materiały z sesji naukowej „Pradzieje i wczesne średniowiecze w dorzeczu Kamiennej 19–20. 10.1986", Ostrowiec Świętokrzyski.

Masini N., Persico R., Rizzo E., 2010. Some Examples of GPR Prospecting for Monitoring of the Monumental Heritage, Journal oaf Geophysics and Engineering, vol. 7, 190–199.

NASA, 2011, Space Satellite Archaeology NASA satellite imaging. http://www.age-of-the-sage.org/space_archaeology/space_satellite_archaeology.html

Orlando P., Villa B., 2011. Remote Sensing Applications in Archaeology. Archeologia e Calcolatori, 22, 147–168.

Potter T.W., Robinson B., 2000. New Roman and prehistoric aerial discoveries at Grandford, Cambridgeshire. Antiquity, 74, 31–32.

Pietrzak R., Rączkowski W., 2006, Zaginione miasto – historyczna zagadka i zdjęcia lotnicze. *Lost city – a historic mystery and aerial photographs*, Archeologia Żywa, 4(38), 15–20.

Praca zbiorowa, 2011, Research and Archaeology Revisited: a revised framework for the East of England, edited by Maria Medlycott. East Anglian Archaeology, Occasional Paper, No. 24, ALGAO East of England.

Rączkowski W., 2002, Archeologia lotnicza – metoda wobec teorii, *Aerial archaeology – a method versus history*, Poznań.

Saturno W., Sever T.L., Irwin D.E., Howell B.F., Garrison T.G., 2007. Putting Us on the Map: Remote Sensing Investigation of the Ancient Maya Landscape. In: Remote Sensing in Archaeology, ed. James Wiseman & Farouk El-Baz, Springer, 138–160.

Sever T.L., 1995. Remote Sensing. American Journal of Archaeology, 99, 83–84.

Sever T.L., 1998a. Arenal Region, Costa Rica. Archaeological Research in the Arenal Region, Costa Rica. http://weather.msfc.nasa.gov/archaeology/arenal.html

Sever T.L., 1998b. Chaco Canyon, New Mexico. NASA Archaeology Research – Chaco Canyon, New Mexico. http://weather.msfc.nasa.gov/archaeology/chaco.html

Ur J., 2003, CORONA satellite photography and ancient road networks: A Northern Mesopotamian case study, Antiquity, 77, 102–105.

Żuk L., 2005, W poszukiwaniu salomonowego rozwiązania, czyli o tym, kto powinien interpretować zdjęcia lotnicze – słów kilka, *Searching for the solution of Solomon, i.e. who should interpret aerial photographs – a few words* [in:] Biskupin… i co dalej? Zdjęcia lotnicze w polskiej archeologii, Nowakowski J., Prinke A., Rączkowski W. (red.), s. 125–144.