High resolution satellite images for archeological applications: the Karima case study (Nubia region, Sudan)

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Abstract
This work presents an approach based on satellite remotely sensed images and Geomatics techniques aimed at supporting the Italian archeological missions that at the moment are active in the Karima Area (Sudan). It's well known that archaeologists often suffer from lack of updated maps useful to geographically manage the observations coming from the field and, possibly, to address or suggest where digging for new excavations. Specifically for this experience QuickBird and ASTER data were acquired and processed to generate a high scale multispectral orthoimage of the area. The spectral properties of the QB orthoimage were exploited with the purpose of obtaining suggestions about the possible existence of stil lhidden archaeological features.
Keywords: Archaeology, Remote Sensing, GNSS, Satellite Orthoimage, Digital Image Processing.

Introduction
Geomatics techniques and methods have recently found research applications in the archeological field [Maktav et al., 2009; Campana et al., 2007; Scardozzi 2007; Lasaponara and Masini 2006; Tan et al., 2006]. Numerous Italian and foreign excavation missions all over the world can find an effective tool in this kind of methodologies especially for the production of updated base and thematic maps of those areas that often are missing an appropriate cartographic support. Once generated, these can then be managed within GIS (Geographic Information Systems) in order to generate old site scenarios (3-D virtual analysis) and to improve the dissemination process. This work concerns the excavations that in the recent decades have been interesting the North Region of Sudan near the town of Karima, on the banks of the Nile, about 350 km north of the capital (Khartoum). The mission is conducted

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by the Egyptologists research group of “La Sapienza” University of Roma and University of Cassino (Italy) [Roccati A., 2008; Vincentelli I., 1999, 2002]. The main purpose of this work was to update and improve the already existing maps of past excavations and to suggest an analysis tool devoted to detect possible future excavation areas, considering Geomatic techniques and digital data.
One Quickbird (QB) image was acquired to generate a high scale orthoimage of the area. Both the multispectral and panchromatic bands were used in order to maintain the information content of the area as higher as possible.
During the excavation campaign carried out in 2005, a GNSS survey was conducted to define a local reference frame with the purpose of:
a) acquire the ground control points (GCPs) needed for the orthoprojection of the image;
b) estimate the transformation parameters from the local reference system (ADINDAN) into the international one (WGS84).
The orthoprojection procedure was conducted using the PCI Geomatica commercial software ver. 9.1. During orthoprojection, the height information was obtained from an hybrid DTM/DSM generated from an ASTER image and integrated, just over the excavation area, with a DTM produced through an existent topographic survey.
Subsequently, the QB orthoimage was used for the identification of possible clues of buried structures, exploiting the spectral content resident in the Blue, Green, Red and Near Infrared bands of the QB data [De Laet et al., 2009].
In this step traditional and basic techniques for image processing were used such as color composite, image enhancement, pansharpening, digital filters. On the basis of the suggestions coming from this step a Ground Penetration Radar (GPR) survey was carried out to better investigate the candidate areas.

Study Area

The area of interest is the Jebel Barkal Area, sited in the north of Sudan, along the Nile between the 3th and 4th waterfall in the Nubian region. This area offers the opportunity of exploiting the photogrammetric and spectral properties of the VHR (Very High Resolution) satellite missions in an archaeological context and, specifically, in these important sites where Italian researchers and institutions are deeply involved (Fig. 1).
The Gebel Barkal name refers to the sacred mountain of Napata (nearby the modern city of Karima), that was belonging to the Egyptian empire during the New Kingdom (XV century BC), when the XXV dynasty was reigning. Napata dynastic city still remained during the Meroitic kingdom and was finally destroyed by the legions of Rome.
The area is nearly flat; heights range between 240 and 280 m above sea level. An isolated hill, the Jebel Barkal, is the only altimetric anomaly around reaching about 370 m.s.l. Two archaeological missions, located at Merowe and Karima, are active at the moment. They are conducted by A. Roccati and I. Vincentelli operating in Sudan for over 70 years on an annual basis [Roccati, 1997].

Materials and Methods

Quickbird Image

The image used during this work was a QuickBird Ortho Ready Standard, expressly purchased from Digitalglobe. The Standard product (Orthoready) was chosen because,

differently from the Basic one, it can be ordered just for the extension of the area of interest and not of the entire scene (16.5 x 16.5 km). This allows a significant reduction of the price. In this case the size of the area covering both the sites of the archaeological Italian missions is approximately 8 x 4 km. As well known the Ortho Ready Standard Imagery is geocorrected, but no topographic correction is taken into consideration. Thus a more rigorous orthoprojection is required as Ortho Ready Standard images have a delivered absolute georeferencing accuracy of 23 m CE90%.
It is worth to remind that QB images have a geometric resolution of 0.61 m for the panchromatic band and 2.44 m for the multispectral one. Multispectral bands are the following: blue (450-520 nm), green (520-600 nm), red (630-690 nm), near-IR (760-900 nm) [Digitalglobe, 2010].

Figure 1 - Test Area – Nubia, Sudan : Karima and Merowe as they appear on the Real Color Landsat Image.

Terra ASTER Image

An ASTER Level 1B image was adopted to generate a DSM (Digital Surface Model) for the study area. ASTER sensor is able to acquire stereoscopic and multispectral images characterized by a varying geometrical resolution and covering a spectral range from 0.556 to 11.32 μm. ASTER can record along track stereo images. Bands 3N and 3B, having a nominal geometric resolution of 15 m and a central wavelength of 0.804-0.807 μm, are devoted to this task. Many scientific papers [Boccardo et al., 2004; Borgogno Mondino et al., 2004] refer about the potential height accuracy of DSM produced by ASTER data. It is said it can varies from 5 m for flat areas up to 25 m for rough areas. (Fig. 2). Even if a free of charge ASTER DSM (global coverage and 30 m resolution) can be obtained from the Earth Remote Sensing Data Analysis Center (ERSDAC) for this work a new one was self produced using the ASTERDTM add-on module of the commercial software ENVI 4.5. ASTER DTM can equally manage both L1A and L1B ASTER images. This choice was done to better evaluate the resulting accuracy of the final product.

Topographic Surveys

In the past decades, along these areas many topographic surveys were performed. For this work, the last detailed survey of the Jebel Barkal area was used. It was carried out by a total station (centimetric precision) during the 2005 campaign guided by Tim Kendall (London British Museum). These data were integrated with the generated ASTER DSM in correspondence with the biggest discontinuity in the area [Roccati, 1997] to improve the local precision and minimize the relief displacement effects during the QB image orthoprojection.

Other previous surveys, primarily descriptive of the temples and palaces of the Pharaohs, were provided by the archaeologists for their geometric homogenization aimed at making them consistent and comparable with the produced orthophotos chosen as the new reference base map [Mitchell, 1996] (Fig. 3).

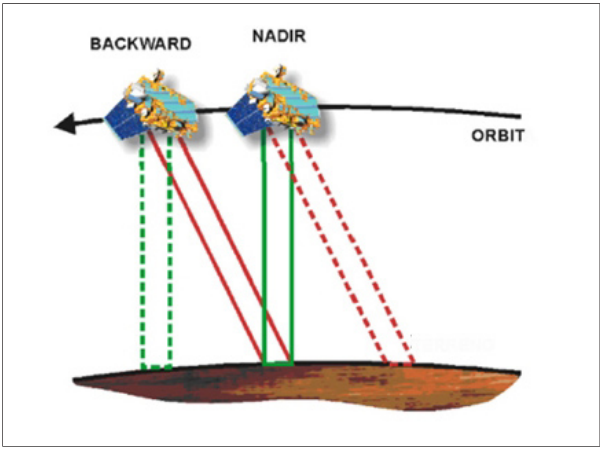

Figure 2 - ASTER Stereoscopic Image Acquisition Scheme.

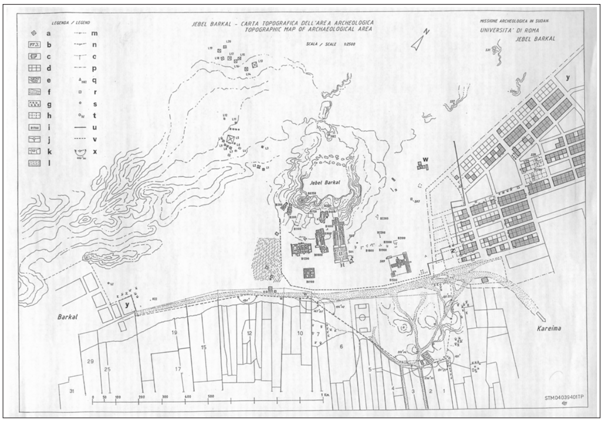

Figure 3 - Examples of Topographic Maps of the area of Jebel Barkal, Karima (Courtesy - University of Rome).

GNSS survey

Firstly, it was necessary to survey an adequate number of GCP in order to proceed with the orthoprojection of the QB image and the orientation of the ASTER stereopair. The expected accuracy of their coordinates was fixed better than the half of QB panchromatic band pixel (30 cm). Such operation was realized by means of a dedicated GPS survey campaign carried out in 2005. The GCP were identified over the QB image in correspondence of natural (e.g. small trees or stones) or anthropic elements (e.g. building corners, walls, crossroads) easily recognizable both on the image and on the field. A higher number of points, respect to the strictly required one for orthoprojection, were selected from the image to face any eventual failure of acquisition at the ground (e.g. inaccessibility, lack of GPS coverage, difficulty of point identification). The GPS survey was made as a static campaign and a post-processing was conducted. The position of each GCP was estimated using the relative positioning strategy [Kuter, et al., 2010]. In this case the goal is the estimation of the baseline vector between the center phase of antenna receivers. If the coordinates of one receiver are known, it is possible to define also the coordinates of the second one [Leica, 2003].

This technique requires:

a) at least two simultaneous operating GPS receivers;
b) some vertices with known coordinates (X, Y, Z).

For this work two single frequency GPS receivers were adopted (Ashtech Promark 2). They were connected to a Compact L1 antenna equipped with Ground Plane. The survey network geometry were designed with the purpose of maintaining the baseline average length around 1.5 km (maximum 7 km). This value was retained suitable for the expected accuracy of the measurements (Fig. 4) [Leick, 2003]. This condition allows to defines a survey strategy based on two networks centered on a known vertex. The unique baseline with a length of almost 7 km was the one between the two known vertexes. For each network, during the survey, a base/master receiver was maintained fixed over the known vertex while the second one (rover) was moved to occupy each of the GCP belonging to the network itself. The occupation time for each GCP was about 25 minutes.

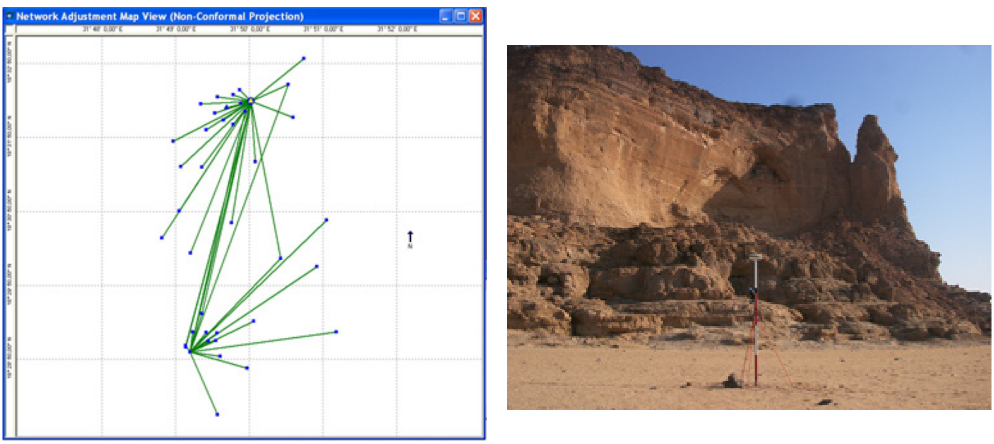

Figure 4 - Final GNSS Adjustment scheme – GNSS Ashtech rover receiver during static session.

GPS data were processed as following described:

- estimation of the coordinates of the master vertexes throughout the PPP (Precise Point Positioning) method;
- estimation of the GCP coordinates in a "local" reference system with a centimetrical level of accuracy, by means of a relative positioning and a network adjustment;
- overview of the network in a global system (IGS05), throughout a coordinate vertex determined with precise point positioning.

The network vertex surveyed in static mode were processed and adjusted. The final coordinates have a good precision (σ < 1cm) but a lower accuracy (< 1 m), with respect to the control point. The points of the adjusted GPS network have the following standard deviations (Tab. 1):

Table 1 - GNSS network Adjustement results.

GPS	σ_N [m]	σ_E[m]	σ_h[m]
Standard deviation	0.05	0.06	0.10

The adjustment of the network baseline were performed with the dedicated software package called *Ashtech Solution*. The coordinates of two points were fixed in order to operate the adjustment and. 32 points were endly estimated. The quality of the point precision position was quite good (Tab. 1), while the absolute position of the entire survey was not particularly excellent (about 2m).

In order to orthoproject the QB image it was necessary to define a global reference system (e.g. ITRF05). The coordinates of the known vertexes have to be defined in this reference system, but how is it possible to do it when existing topographic points are not present in the area?

It would be possible to define new ones using, even in this case, the relative positioning approach (through baselines). Unfortunately the lack of near GPS permanent stations did not permit this solution. Thus an alternative method was selected: the Precise Point Positioning (PPP) [Chen and Gao, 2004].

Briefly, the PPP procedure is an un-differenced technique, where the observations (pseudorange and carrier phase) are not differenced, but the positioning is obtained modeling all possible biases (clock delay, ionosphere, troposphere, ephemerides, antenna phase centre, etc…) [De Agostino et al., 2008].

Some models are estimated by dedicated services (e.g. International GNSS Service IGS), some others have to be estimated through a long continuous raw data subset.

In order to collect the data suitable for PPP solution, one of the fixed points (situated in Karima) was acquired with one continuous session lasting 36 hours.

Two kind of different PPP procedures in order to estimates the position of the known points were conducted. The first PPP solution on L1 was estimated through a web service offered by the Canadian Natural Resource called CSRS-PPP (Fig. 5), (http://webapp.csrs.nrcan.gc.ca/index_e/products_e/online_data_e/online_data_e.html).

The CSRS-PPP procedure uses an undifferenced and combined approach, where a frequency combination, if available, could be used in order to obtain some advantages (e.g. remove bias, fixing ambiguity, etc…). This procedure is an online service and it requires only the RINEX files of the occupied points.

CSRS-PPP

(Processing Software Version: 1.04 246)

Processing Summary for BASE3361.06O

Data Start		**Data End**
2006-12-02 06:32:55.00		2006-12-03 19:08:35.00
	Apri / Aposteriori Code Std	
	1.0m / 1.117m	
Observations	**Frequency**	**Mode**
Code	L1	Static
Elevation Cut-Off	**Rejected Epochs**	**Estimation Step**
10.000 degrees	0.00 %	Same as Input RINEX File
Antenna Model	**APC to ARP**	**ARP to Marker**
	0.000 m	0.000 m

(APC = antenna phase center; ARP = antenna reference point)

Estimated Position for BASE3361.06O

	Latitude (+n) (dms)	**Longitude (+e) (dms)**	**Ell. Height (m)**
ITRF05	18 32 19.0638	31 50 01.3320	262.347
Sigmas	0.022	0.024	0.057
Apriori	18 32 19.089	31 50 01.199	264.924
Estimated - Apriori	-0.787 m	3.892 m	-2.577 m
Orthometric Height CGVD28 (HTv2.0)	_NOT_DEFINED_	(click here for model and accuracy)	

(Coordinates from RINEX file used as apriori position)

Figure 5 - Example of CSRS-PPP Procedure final report.

The second PPP solution of these points was also performed using the commercial package *Waypoint Grafnav 8.10*. The single frequency data was also here considered, as well as the ephemerides and the error clock file.

In this case, it is necessary to load the available model of bias (e.g. inosphere delay using the IONEX file), in order to improve the quality of the final solution.

The strategies of calculus of Grafnav and CSRS are lightly different and they led to have different results. In particular the Grafnav solution has a worse distribution than the CSRS. In both the cases, the results are satisfactory, respect to the precision of the orthophoto. The differences between the two solutions are shown in Table 2.

Table 2 - Coordinates Differences between Waypoint Grafnav 8.10 and CSRS-PPP.

ΔN [m]	ΔE[m]	Δh[m]
-0.246	0.019	0.71

Unfortunately the obtained accuracy was not excellent (the use of the only L1 does not help to completely remove all biases (e.g. Ionospheric delay)), but surely suitable for a 1:5000 scale cartography.

Image pre-processing

The Quickbird image processing was carried out following the workflow described in Figure 6.

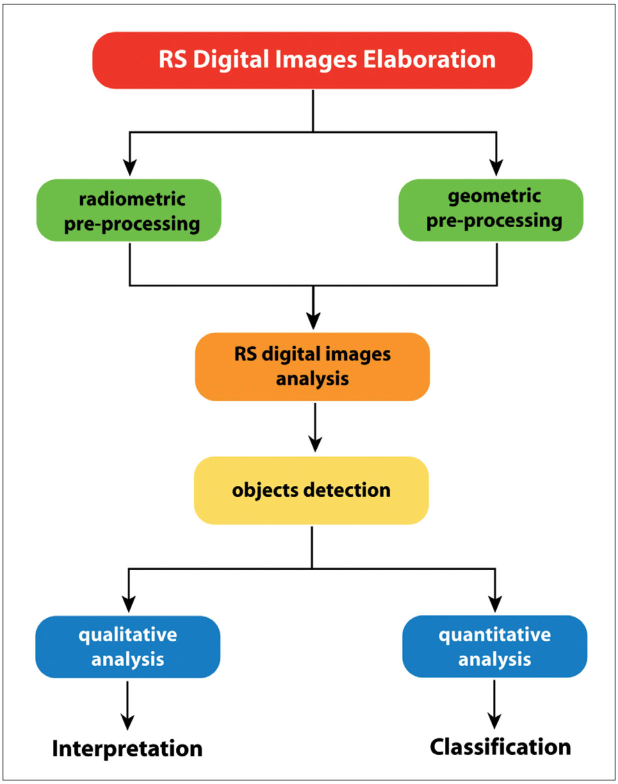

Figure 6 - Remote sensing data process elaboration scheme.

Geometric Pre-processing

Past experiences demonstrate that a better horizontal accuracy of orthoimages coming from VHR satellite data can be obtained projecting them through a rigorous sensor model [Boccardo et al., 2003]. Unfortunately the Ortho Ready Standard products do not permit this strategy, being already processed data. Anyway the original accuracy of the delivered product (see above) can be improved exploiting the RPC (Rational Polynomial Coefficients) [Boccardo et al., 2005] supplied together with the images. Using the RFM (Rational Function Model) available inside many commercial softwares and refining the solution given by the RPCs with the adoption of some GCPs and an adequate DSM it is possible to improve the final accuracy of the Ortho Ready Standard images. For this work the OrthoEngine module of PCI GEOMATICA Ver. 9.1 was adopted. 26 GCPs (surveyed during the GNSS campaign) and the previously generated DSM were used for the process (Fig. 7).

The accuracy of the final orthoimage (the Pan-sharpened one) is defined by the obtained RMSE (Root Mean Squared Error) as shown in Table 3. Values suggest that the orthoimage can be retained suitable for 1:5000 scale map (if compared with the Italian technical specification for map production).

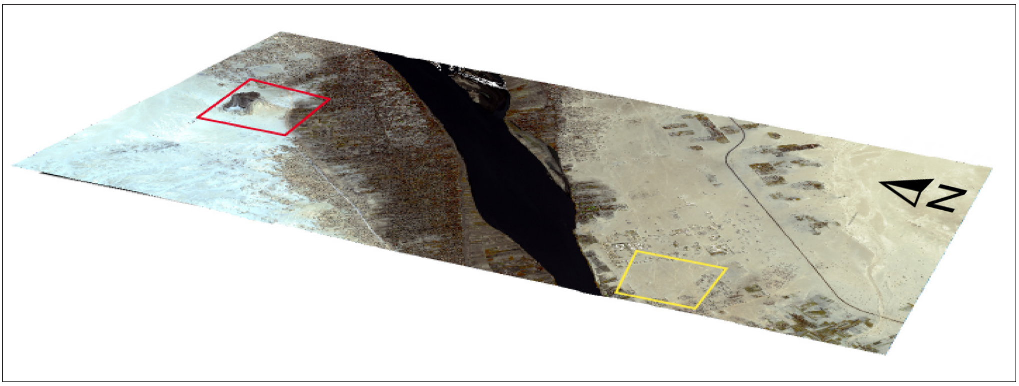

Figure 7 - Final QB True Color Orthoimage showing the test sites of Karima and Merowe.

Table 3 - Orthoprojection RMSE.

PCI ORTHO	*GCPs*	*CPs*
RMSE (x)	1,63	1,52
RMSE (y)	0,44	0,49
RMSE TOT	**1,69**	**1,60**

Radiometric Pre-processing

The radiometric corrections applied to the Ortho Ready Standard products include: relative radiometric response between detectors, non-responsive detector fill, and a conversion for absolute radiometry. The sensor corrections account for internal detector geometry, optical distortion, scan distortion, any line-rate variations, and mis-registration of the multi-spectral bands (http://www.eurimage.it/products/quickbird.html). Nevertheless the QB Ortho Ready Standard imagery comes in the hands of the user in terms of Digital Numbers represented in 16 or 8 bits per pixel. The QB image used for this work was a 16 bits one, thus in order to recover the at-the ground reflectances both a conversion from DN to radiances and an atmospheric correction were performed. As far as the radiometric calibration is concerned it was performed using the GAIN values (see Table 4) as estimated by NASA [Holekamp, 2006]. Afterwards, atmospheric correction and at-the-ground reflectance calibration was operated by the FLAASH module of ITT ENVI (see Table 5).

Table 4 - Average Spectral Radiance Calibration Coefficients (Holekamp, 2006).

Bandwidth FWHM (µm)	*NASA Team Estimate (W/m² sr µm DN)*	*Quickbird Provided (W/m² sr µm DN)*	*% Difference*
1 0.445 – 0.510	0.26 ± 0.02	0.236	9.2%
2 0.500 – 0.595	0.16 ± 0.01	0.145	9.4%
3 0.620 – 0.690	0.19 ± 0.01	0.179	5.8%
4 0.755 – 0.875	0.14 ± 0.01	0.135	3.6%

Table 5 - Atmospheric correction parameters.

FLAASH Parameters	Value
Sensor type	Quickbird
Data Type	BIL
Pixel size	2.4 m
Ground elevation	0.3 km
Scene centre Lat/Long	18.54º N, 31.80º E
Visibility	40 km
Sensor altitude	450 km
Flight date & flight time	03/09/2003 12:49:00
Atmospheric model	Tropical
Aerosol model	Rural
Water vapour retrieval	-
Spectral polishing	No
Wavelength calibration Adv parameters	Yes Common

Image processing and interpretation

The new multispectral pansharpened orthoimage having a pixel size of 0.61 m, was successfully used for terrain investigation aimed at the identification of archaeological potential evidences. The main idea is that anomalous underground features can condition the physical properties of the surface thus their reflectances. These radiometric anomalies can be recorded by the optical sensor exploiting information coming also from spectral bands different from the visible one. According to high resolution multispectral images, the added value is connected to the availability of the near infrared band. More improvements could come from SW infrared bands (highly sensible to surface water content); but at the moment there is no high resolution satellite equipped with such a sensor.

Nevertheless some underground evidences could be recognized through image processing techniques operating over the 4 available bands. In particular, histogram stretching, density slicing, filtering (high-pass or edge detectors) and image pan-sharpening can be successfully used for this purpose. Some examples, concerning the study area are presented.

Pan-sharpening

This technique is useful to merge the spectral content of lower resolution multispectral bands (XS) with the highest geometrical content of the panchromatic band. For Quickbird images, the effect is the generation of 4 spectral bands that radiometrically correspond to the original 2.44 m XS bands, but that have a geometric resolution of 0.6 m as the panchromatic one (PAN). Image interpretation can be highly improved in this way permitting a more effective data analysis (Fig. 8). For this work the adopted pan-sharpening algorithm was a basic one using the transformation between the RGB (Red, Green, Blue) and HSV (Hue Saturation and Value) color spaces with injection of the PAN band.

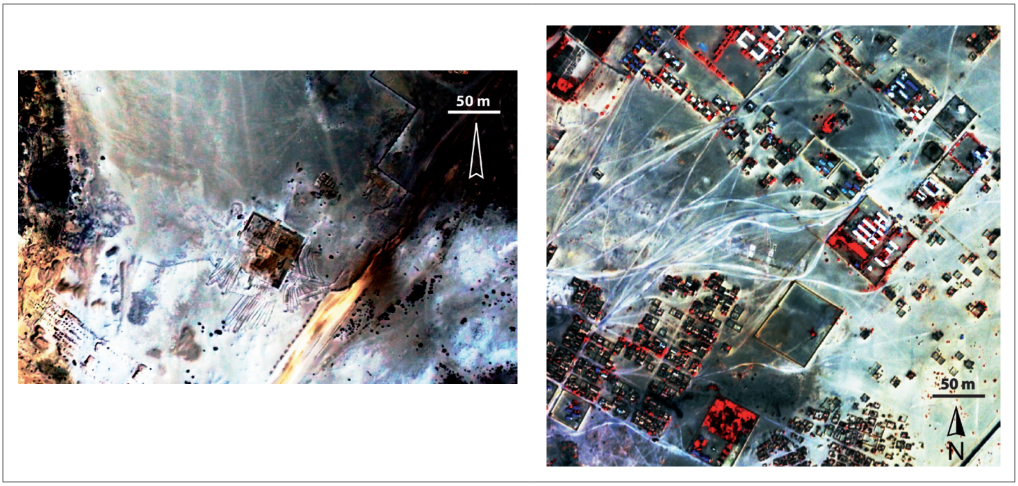

Figure 8 - Example of Pan-Sharpening in the Gebel Barkal and Merowe test site.

Histogram stretching

This operation permits to enhance those radiometric ranges of the image that are retained containing the features of interest. Figure 9 shows how just registering the values of brightness and contrast of the displayed bands interesting particulars, previously hidden, can be observed.

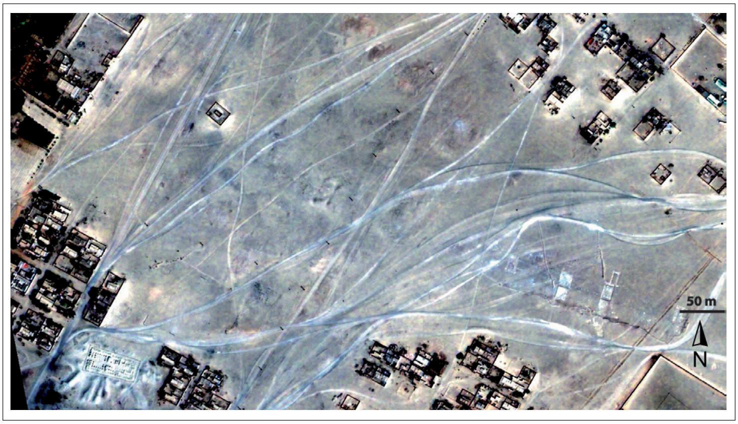

Figure 9 - Effects of the histogram stretching aimed at enhancing the radiometric anomalies of the area (Merowe test site). The displayed RGB composite was obtained from the NIR, Red, Green bands of the pan-sharpened image.

Filtering

High pass digital filters can be applied to the images to evidence the radiometric borders (Fig. 10). The filter effect can be compared to a map where the radiometric borders represent the hidden archaeological structures (e.g. temple walls, palaces…).

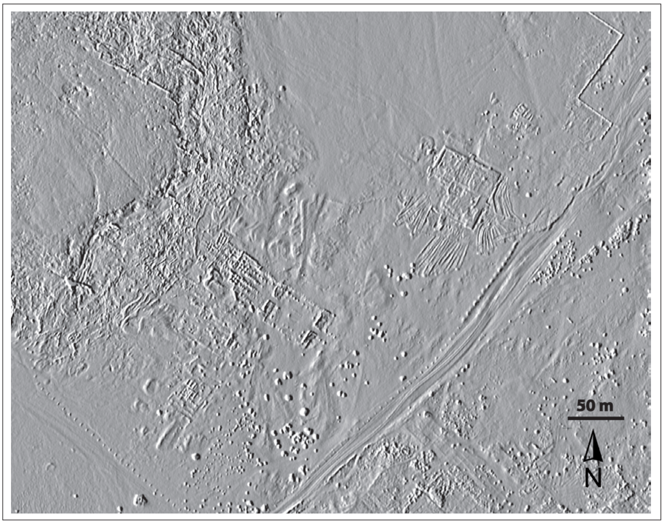

Figure 10 - Applying directional filtering for the anomalies detection.

Density slice

This technique is able to divide the radiometry of a single band into class ranges according to the user interest. Each class corresponding to a radiometric interval of the image histogram is represented by a different color generating a sort of classified image (Fig. 11).

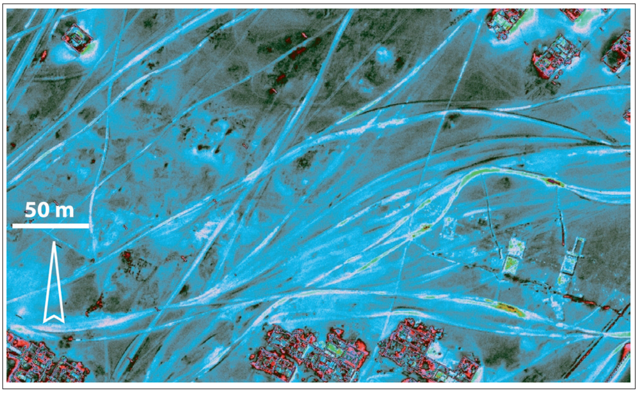

Figure 11 - Density slice on the excavation area of Merowe that highlights how the whole area is characterized by the presence of underground structures.

Three-Dimensional Site Modeling

Using a DSM, the orthoimage can be draped over it to generate a 3D model for a better area analysis (Fig. 12). The 3D model can be dynamically explored and it can be possible to create animated simulations useful for a better presentation of the obtained results.

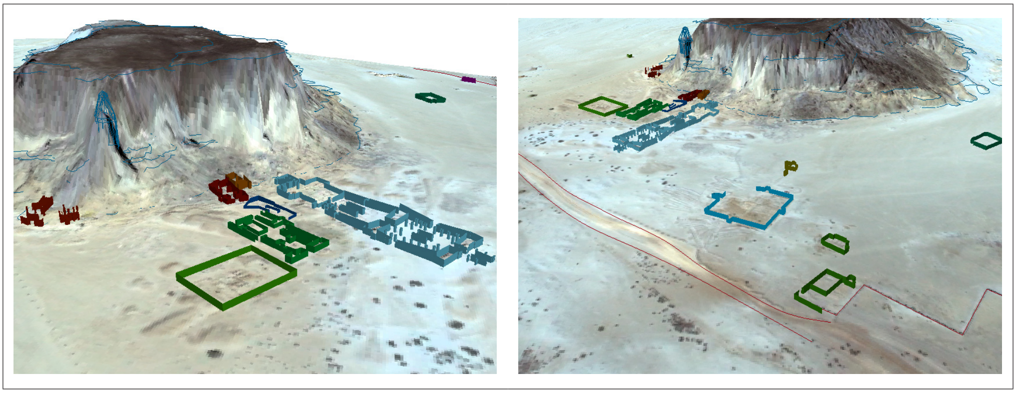

Figure 12 - 3D representation in GIS environment with the overlaying of old and new discovered artifacts.

Thematic Maps and New Excavations Results

This simple processing of remotely sensed data widely used over the available image, represented a great input and help in addressing the successive archaeological excavation campaigns. The desert areas are without any doubt fascinating sites for testing the opportunities of spectral data associated to high geometric resolutions. Nevertheless it cannot be forgotten that VHR satellite orthoimages represent also an updated cartographic basis for all of that areas of the world that suffers from a lack of high scale maps. Looking at them some important information, previously ignored, can be made clear. A first important goal was identifying on the orthoprojected quickbird image some ground anomalies. Over one of these areas was set the new excavations campaign and a new artifact was discovered during the 2007 (Fig. 13).

Figure 13 (left) - Excavations in the 2007 campaign after the Karima test site image processing - (right) floor discovered after 2007 excavation in the Merowe test site (thanks to the radiometric anomaly report from QB image).

Another important result was that we noticed that in the Jebel Barkal area the Nile river has played an important role during its life. It has modified its path and the people who lived close to the river had to move its settlements. In the survey campaign carried out in 2007, a Georadar analysis, which allows to investigate the underground from a few centimeters to hundreds meters, has been conducted (Fig. 14).

The interest was focused in the possibility of reconstruction of old environments as settlements or any kind of buildings. Some hidden morphologies were reconstructed by combining a GPS connected to the Georadar, the QB orthoimnage and a GIS. Starting from these data, several maps of anomalies, useful for future archaeological campaigns, were generated.

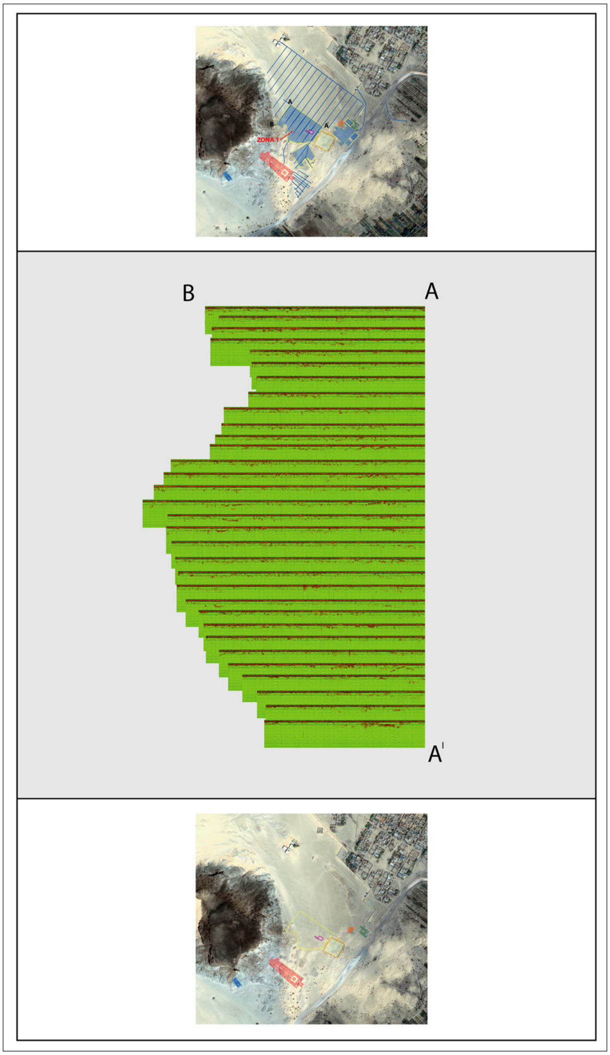

Figure 14 - GeoRadar survey in the Gebel Barkal Area.

Conclusions

According to the preliminary remarks and the results achieved, it is possible to state that VHR satellite images represent a suitable tool both for map production and archaeological evidence investigation.

As far as mapping capabilities of such data are concerned, the horizontal accuracy obtained for the Quickbird orthoimage makes it comparable to a 1:5000 scale map. The orthoimage can be effectively used to guarantee congruence between all of the ground surveys and, in the meantime, to make them easier to be read and interpreted.

ASTER images can be considered a valid and cheap product useful to generate a medium accuracy DSM (10-18 m absolute vertical accuracy, 7 m relative accuracy). This can be successfully used to generate orthoimages (limited accuracy is not a problem in this application as the image is taken from a very high position). Moreover it can also be used to produce 3D models aimed at area interpretation (regional analysis).

The orthoprojected satellite image was finally used as basis for all of the field surveys performed up to now in the Jebel Barkal Region, including buildings, temples and main topographic features. A global data integration was thus possible inside a GIS (Geographic Information system).

In the future, the diffusion of high resolution stereo images [Capaldo et al., 2012] , the improvement of the GPS survey, traditional topographic and remote sensing techniques will certainly provide more effective tools to this interesting field of the research.

Moreover the use of a new active high resolution radar active sensors will be an excellent tool for the discovery and study of the excavations. For example Cosmo-Skymed working with all whether condition (day, night with any cloudy coverage) with high geometric resolution and was born out to observe the "Mediterranean" area where is the highest density of the Archaeological sites in the world [Di Iorio et al., 2010; Coletta et al. 2008].

Cooperation projects on archaeological and geo-archaeological development will gain substantial advantages from the correct terrain representation made available by this type of instruments. GIS environment can be then used to manage and represent data coming from different sources.

Acknowledgements

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