Integrated technologies and methodologies for the reconstruction of the ancient topography of Hierapolis in Phrygia and its territory (Turkey)

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Abstract: This paper concerns use of integrated technologies and methodologies for the urban layout reconstruction of the Roman and Byzantine city of Hierapolis in Phrygia (Pamukkale, south-west Turkey), and for the study of the ancient topography of its territory. The researches, started in 2003, in cooperation with the Italian Archaeological Mission, are based on the integration of systematic archaeological survey, geophysical prospecting, topographical survey with GPS systems, use of aerial photos, analysis and processing of high resolution and multi-temporal satellite images. In absence of up-to-date maps with a good scale for archaeological survey, satellite images have been orthorectified in order to create space-maps. The orthoimages and the numerical derived maps, with technical specification own of maps for archaeological research in scale 1:10,000, become layers in the GIS and webGIS of Hierapolis and its territory.

Zusammenfassung: Dieser Beitrag behandelt die Verwendung neuer integrierter Technologien und Methoden für die Rekonstruktion der Struktur der römischen und byzantinischen Stadt Hierapolis in Phrygien (Pamukkale, im Südwesten der Türkei) und für die Untersuchung der alten Topographie ihres Gebietes. Die 2003 begonnenen Untersuchungen sind Teil des Projektes der Italienischen Archäologischen Mission und basieren auf der Integration von systematischen archäologischen Erkundungen, geophysikalischen Prospektionen, topographischen Aufnahmen durch GPS-Systeme, Luftaufnahmen, Analysen und Verarbeitung von hochauflösenden Satellitenbildern aus verschiedenen Jahren. Da es keine aktuelle Landkarte gab, die in einem für die archäologischen Erkundungen gut geeigneten Maßstab vorlag, wurden hochauflösende Satellitenbilder ortho-rektifiziert, um “Raum-Karten” zu realisieren. Von den ortho-rektifizierten Bildern wurden auch Karten im Maßstab 1:10000 realisiert, die spezifische Merkmale der für die in den archäologischen Untersuchungen benutzten Karten aufweisen. Die ortho-rektifizierten Bilder und Karten wurden als Basis für das GIS und WebGIS der Stadt und des Stadtgebietes benutzt.

Keywords: Landscape Archaeology, Remote Sensing, Archaeological Survey, GPS, Cartography.

The Hierapolis of Phrygia Survey Project

Since 2003, the Institute for Archaeological and Monumental Heritage of the Italian National Research Council (CNR-IBAM) has conducted archaeological researches in Hierapolis of Phrygia (Pamukkale, south-west Turkey), in cooperation with the Italian Archaeological Mission, finalized to the reconstruction of the urban layout of the city and to the study of the ancient topography of its territory (Fig. 1). The research is based on the integration different non-destructive study methods and technologies: systematic archaeological survey, geophysical prospecting and processing, analysis and interpretation of multi-temporal high resolution satellite images (SCARDOZZI 2007a and 2008a).

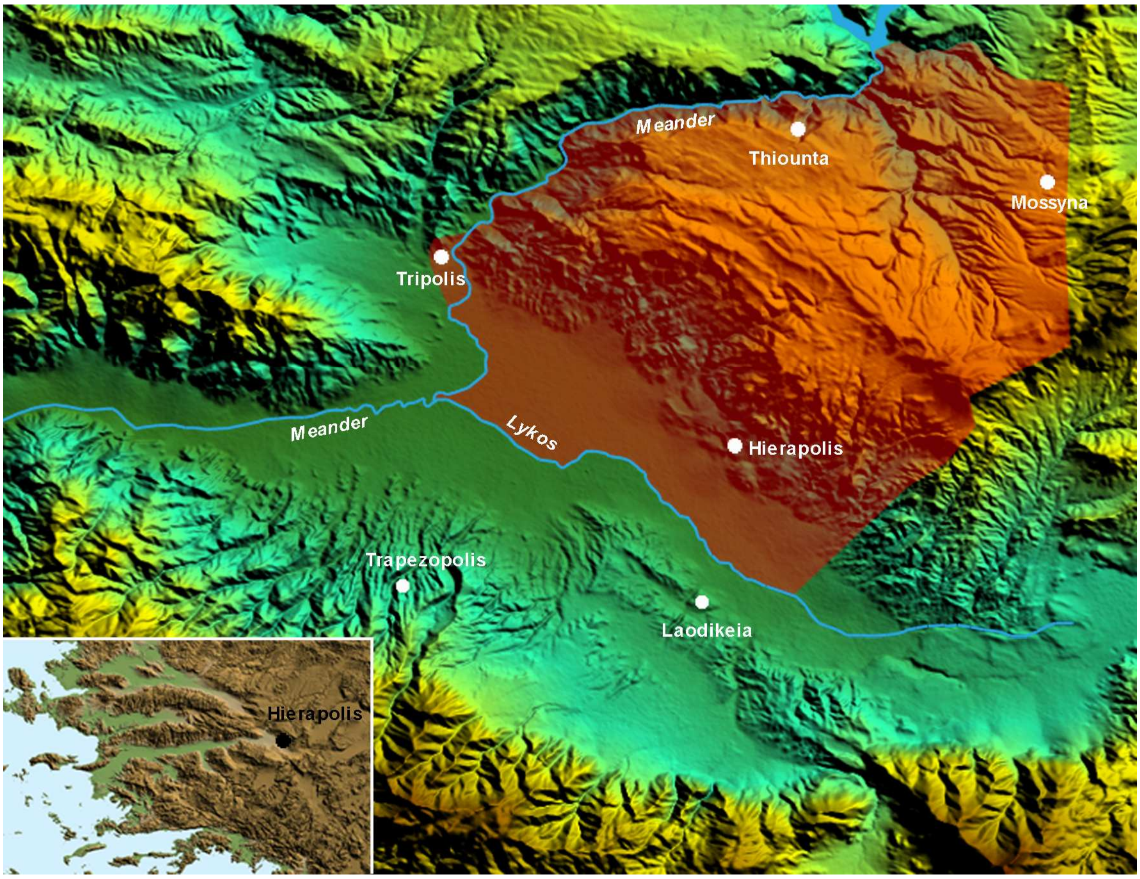

Fig. 1 - ASTER DEM of the Lykos and the Meander valleys: in red the area surveyed in the Hierapolis of Phrygia Project.

The latter have compensated the limited availability of aerial photos and up-to-date maps on an adequate scale for field work. Therefore some satellite images of QuickBird-2 and Ikonos-2 (with a ground resolution re-sampled to 0.60 and 1 m in panchromatic mode, and 2.40 and 4 m in multispectral mode) are processed and used to find traces and anomalies linked to buried archaeological structures, and as base-maps during field work. In fact, thanks to their high ground resolution, they are particularly suitable in detailed archaeological surveys aimed at the study of contexts limited in extension and, for this reason, they have been used in each phase of the research: from the activities on the field to data elaboration and management up to the presentation of the results; the analysis and the interpretation of traces and anomalies concerning partially or completely buried archaeological features, constantly verified on the ground and compared to the available aerial photos, have allowed the identification and the spatial characterization of several archaeological evidences. Images have also allowed the detection of paleo-environmental elements and contributed to the reconstruction of the ancient landscape; regarding excavated or partially emerging monuments or archaeological sites, images have been used in order to document and contextualize them. In some cases, the processing of satellite images acquired in multispectral mode, in which the measured radiation is divided in four bands including the spectrum of the visible (blue, green, red) and the near infra-red, made it possible to better locate archaeological and paleo-environmental features (LASAPONARA et al. 2008a and 2008b). Some types of elaborations and fusion between panchromatic and multispectral data were tested, in order to highlight different archaeological anomalies and traces and to recognize elements that can provide a reconstruction of the ancient landscape (see below); in particular, for the geological characteristics of the territory of Hierapolis panchromatic images are better for the detection of damp-marks, while red and infra-red channels are better for the detection of crop and soil-marks.

For research in Hierapolis and its territory the use of multi-temporal remote sensing data, not only limited to the most recent years, was very important (Fig. 2).

Fig. 2 - Hierapolis in a Corona KH-4A photo of 1968 and in a QuickBird-2 image of 2007.

Because of the unavailability of old aerial photos, some images taken in the 1960s and 1970s by American reconnaissance satellites Corona KH-2, KH-3, KH-4A and Hexagon KH-9 were acquired, with a geometric resolution between 2.74 and 9 m (SCARDOZZI 2008b); unfortunately, very high resolution space photos of Corona KH-4B and Gambit KH-7 systems (with ground resolution between 0.60 and c. 1.80 m) are not available for the Hierapolis territory. The analysis and interpretation of these historical photos, properly geo-referenced in the GIS of Hierapolis, were very useful during research, because it was possible to acquire abundant data for the reconstruction of the urban layout and of the ancient topography in its territory. In fact, they show Hierapolis and the surrounding landscape before a few important transformations of the last decades, such as the construction of buildings that have destroyed ancient remains (Fig. 3), the creation of infrastructures, the expansion of modern villages, and the diffusion of mechanized agriculture.

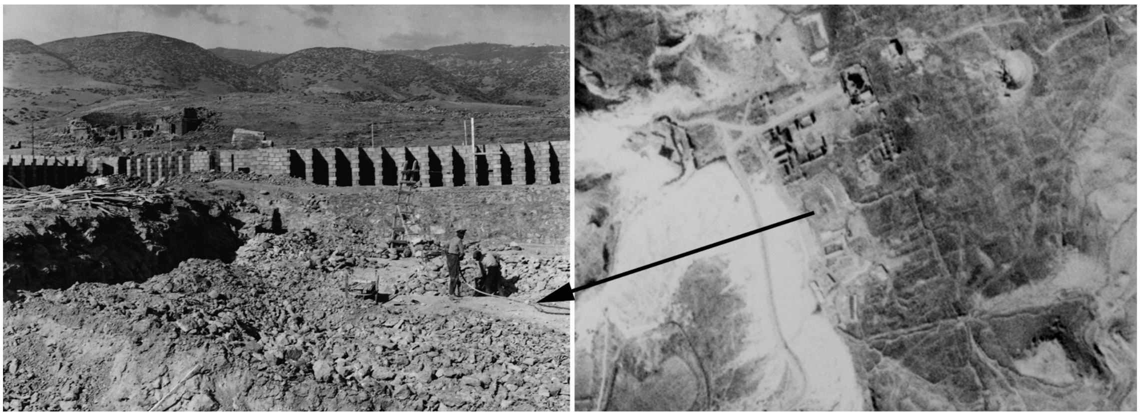

Fig. 3 - Works for the building of the Palmiye Otel in 1967; the same area in a detail of a Corona KH-4A photo of 1968.

Traces and anomalies found in older satellite images were constantly confronted with the modern situation documented by the recent ones of QuickBird (of the years 2002, 2003, 2005 and 2007) and Ikonos (2004). For example, in the Corona KH-4B photos of 1968 several traces of the ancient road network are clearly visible, more than today, especially in the southern area of the city; in fact, the images show the ancient remains still little affected by modern structures built in the following years, such as some hotels in the west side of the urban area. The geo-referencing of these photos in the GIS of Hierapolis, together with the measurements taken on the ground, enabled the vectorization of all the traces and remains of the road network in the archaeological map of the city. The same images also show clearly the situation before the construction of modern structures at the northern tip of the North Necropolis, and in the area between the Frontinus South Gate and the South Necropolis: the traces of the main roads northward and southward are visible. Furthermore, the landscape around the ancient city has been transformed in the last forty years: for example, in the Corona images the white calcareous formations covering the slope that from the terrace of Hierapolis descends towards the Lykos valley and the village of Pamukkale appear less extensive than today and some routes, that climbed along this slope, are clearly visible; moreover, the hills east of the ancient city in 1960s are still not covered by coniferous woods and in the images some ancient quarries of travertine are visible, along with the remains of the old road that from Hierapolis climbed to the large plateau north of the city. The USA reconnaissance space photographs also provided an important contribution for research in the territory of city. Particularly, satellite images Corona and Hexagon have supplied important data about ancient orthogonal land divisions present in the northern part of the plateau north of Hierapolis, showing ancient limits better preserved than today, when some of them were destroyed because of new buildings and agricultural works. The images of the 1960s and 1970s also show the traces and the remains of the main ancient roads leading out of the city, some ancient quarries of travertine and

alabaster north-west Hierapolis, now partially destroyed by the revival of extractive activities, and many other archaeological evidences are documented in a situation better preserved than nowadays. During field work, a constant verification of the geo-referenced traces and anomalies found in all the satellite images (historical and recent) was carried out, in order to specify their real pertinence to archaeological elements, the interpretation and, if possible, also the chronology, avoiding misunderstandings and mistakes; for the detection of archaeological features in the images, automatic systems were not used, but only the verify on the ground and the experience of the visual analysis, inspection and interpretation. During survey, precise topographical measurements with the use of Total Station and GPS in static and RTK mode allowed to record all architectural remains well preserved in situ and visible on the surface; with differential GPS very high resolution Digital Elevation Models of limited areas of the city were also realized. Data obtained by comparison and integration of collected data with the aerial photos (particularly oblique from the helicopter and an aerostatic balloon) were very important too, because useful for the documentation of the archaeological areas, in helping to understand some topographical situations and the articulation of monumental complexes (Fig. 4).
In 2007-2008, in order to gather further knowledge about the less well-known sectors of the urban area, archaeological surveys and remote sensing data have been integrated with geo-magnetic surveys and with the use of the Ground Penetrating Radar (GPR); this methodological and multi-disciplinary approach, based on the integration of different remote sensing technologies, was particularly necessary in some areas of the city, where colluvial and alluvial sediments and a thick layer of limestone, which covers the western side of Hierapolis from the Medieval Age (generated by the calcareous water from the thermal springs along the seismic fault that run into the ancient urban area), prevented the observation of the articulation of the urban layout. Geophysical surveys tested in various points with different geo-morphological characteristics allowed to identify and locate traces of features invisible on the surface, like paved streets, squares and remains of buildings (Fig. 5); they therefore contributed to the reconstruction of the original plan of the city.

Fig. 4 - Low-oblique air photo from an aerostatic balloon: remains and traces of the regular road pattern in the central area of Hierapolis are visible.

Fig. 5 - Prospecting with GPR in the central area of Hierapolis: traces of a buried ancient building (geo-referenced in the archaeological map of the city) were identified in an area where on surface are visible any remains.

In the QuickBird satellite images used for the research project, a poor visibility of the archaeological traces highlighted by the micro-relief (shadow sites) was noticed, because of the impossibility of the stereoscopic view; in fact, even if many images were acquired in the morning, with the sun still low on the horizon, so that many height differences result to be highlighted by long shadows, it is not in any case possible to appreciate the slightest altimetric variations. Initially, in order to avoid this kind of difficulty, some anaglyphs were processed experimentally; in fact, they were obtained by duplicating the same satellite image, with an optical artifice that allows a quick perception of the third dimension, without achieving a real stereoscopy. Moreover, digital models of the ground, with a middle-high resolution, have been processed and are based on SRTM (Shuttle Radar Topography Mission) data and on a stereo pair taken by Terra satellite with ASTER (Advanced Spaceborne Thermal Emission and Reflectance Radiometer) sensor in 2004. On these data, both the panchromatic and the pan-sharpened images have been geo-referenced, in order to associate archaeological traces to ground morphology. In this way, it was possible to study the territory in third dimension. A stereo pair taken by the satellite Ikonos in 2004, has also been used; these images have been processed to get epipolar panchromatic images. From these images, using automatic techniques of auto-correlation, typical of digital photogrammetry, a high resolution DEM was extracted; it was draped with the panchromatic satellite images and with real colour and false infra-red colour pan-sharpened images. Moreover, it was possible to display an anaglyph of the epipolar images that provided a real stereoscopy in which the micro-relief seems to be strongly exalted; even the slightest orographic variation can be caught, with the possibility of measuring differences in elevation. 3D models of the ground, on which satellite images are draped, are particularly useful, not only for the study of the territory, but also for the presentation of research results, both with static images and flight simulations (see below); in fact, is possible to show the archaeological evidences geo-referenced on the DEMs in their proper altimetric position.

Integration between different methodologies and technologies was fundamental in the Hierapolis of Phrygia Survey Project for the knowledge of city plan and its transformations in the main historic periods (Hellenistic, Roman, Byzantine, Ottoman). The systematic archaeological surveys and geo-physical prospecting, together with the constant analysis of the satellite images, space and aerial photos, and the traditional study of ancient maps (Fig. 6), allowed to recover abundant data on the urban layout of Hierapolis, previously not systematically studied; these heterogeneous data are included in the numerical cartography of the city, elaborated in a scale of 1:1,000 in cooperation with the architects of the Polytechnic Institute in Turin (D'ANDRIA et al. 2008; SCARDOZZI, SPANÒ 2008), and in the webGIS of Hierapolis, where the archaeological map is the basis of navigation on the urban area and the necropolises together with the QuickBird satellite image of 2005 (CASTRIANNI et al. 2008).

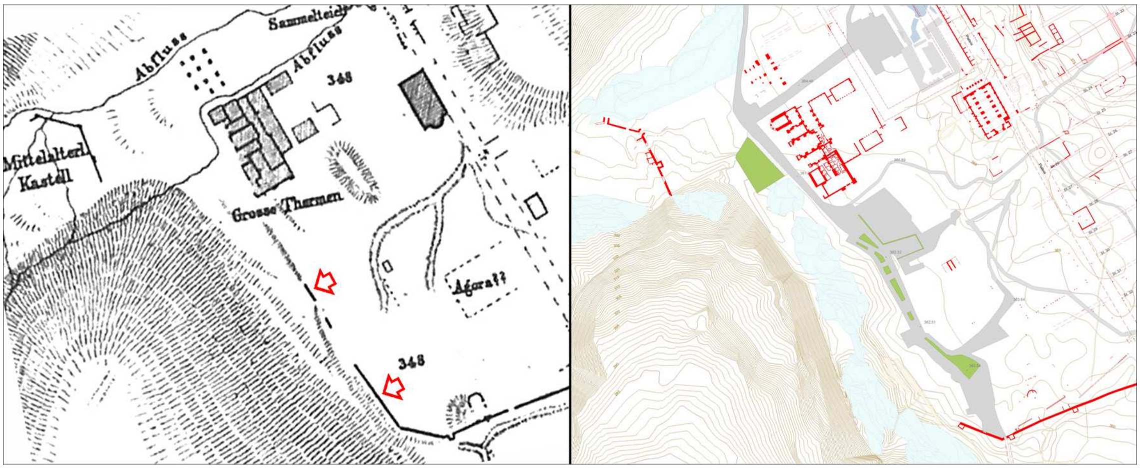

Fig. 6 - City maps of 1898 and 2008: the red shadows on the left image show remains of the Byzantine city walls now destroyed.

Sometimes the new data acquired from archaeological surveys and from satellite images processing had directed the strategies of the archaeological excavations. The discovery of the processional route to the Martyrion of St. Philip is surely the main example of this research methodology; the traces and anomalies linked to the route were initially recognized in the satellite images and later verified on the ground; finally, the ancient structures were excavated (SCARDOZZI 2007b).

The archaeological surveys of 2005-2006-2007 were extended to the territory that in ancient times was under the control of Hierapolis, with the aim of reconstructing the settlement pattern; this is a large area that concerns the eastern part of the Lykos valley and the broad plateau north of Hierapolis on the western slopes of which lies the terrace on which the city was built. For research in the territory, satellite images replaced aerial photos and also integrated cartographies used in field work and in the GIS. In fact, while on the urban area and the necropolises a numeric cartography on a large scale is available, only raster Turkish maps on a scale 1:25,000, drawn in 1970s and updated in 1990s, are available on the territory; they are poorly detailed, therefore scarcely useful particularly in the field work. Consequently, space-maps of some sectors of the territory have been created, with tolerances of cartographies in a scale between 1:10,000 and 1:5,000, thanks the orthorectification of satellite images; a cartography for archaeological research (in the tolerance of a 1:10,000 scale) was also produced and vector elements (modern urbanization and topography, hydrology, archaeological evidences and traces, etc.) were also extracted from a high resolution orthoimage of Ikonos (see below).

During researches in the Hierapolis territory, this numeric cartography aimed at archaeological research, geo-referencing satellite images and space-maps were used in the GIS and during field work within a system, called Ulixes, developed to provide support to archaeological survey, speeding the positioning and documentation of archaeological presence. The system allows to navigate on cartographies (vector and raster), vertical aerial photos and high resolution satellite images visualized on a Tablet PC linked to a GPS receiver with metric precision; during field work, in the event of an archaeological discovery, it is possible to memorise its position and connect the geographical coordinates as metadata consisting of a record with a detailed description of the type of feature (DI GIACOMO, DI GIACOMO, SCARDOZZI 2008).

During archaeological surveys, in the area immediately surrounding Hierapolis, numerous ancient travertine, white marble, breccia, onyx and alabaster quarries were identified (Fig. 7), used extensively in the buildings of the city and the necropolises. Again in the area immediately surrounding the city and in the plateau north of Hierapolis, evidence of intensive occupation of the territory were found, with rural villages and settlements of medium and small size, identifiable as farms, with installations for oil and wine production and spanning over a period from the late Hellenistic - Early Imperial ages to the Byzantine epoch; sometimes the remains visible on the surface are insignificant, but the processing of the satellite images in some cases makes it possible to highlight traces of the buried ancient structures (see below Fig. 12).

Fig. 7 - Trenches of ancient travertine and alabaster quarries in the territory north-west of Hierapolis in a QuickBird image of 2005.

The aqueducts, which brought water to Hierapolis along three main routes, from the north, north-east and east, have been identified, documented and positioned (Fig. 8). Between 6 and 13 km long, they consisted of terracotta pipes of medium size, in some cases simply buried in the earth, in others laid in hollows carved out of the rock or carved stone supports; they took drinking water from springs located immediately below the brow of the plateau to the north of the city.

Fig. 8 - One of the aqueducts of Hierapolis: the shadows show the cut in the rock for the terracotta pipes.

Fig. 9 - Detail of the Tabula Peutingeriana with the roads from Tripolis to Hierapolis and from the second city to Laodikeia.

The main ancient roads leading out of Hierapolis were also reconstructed, particularly those connecting the city to Tripolis to the north-west and Laodikeia to the south-west, mentioned both in the Itinerarium Antonini and in the Tabula Peutingeriana (Figs. 9-10). The first road, about 19.5 km long, was partially retraced by the old way that connected the modern villages in the western sector of the Lykos valley; this road, documented also in the Corona photo of 1968, is today partially modified and paved in asphalt.

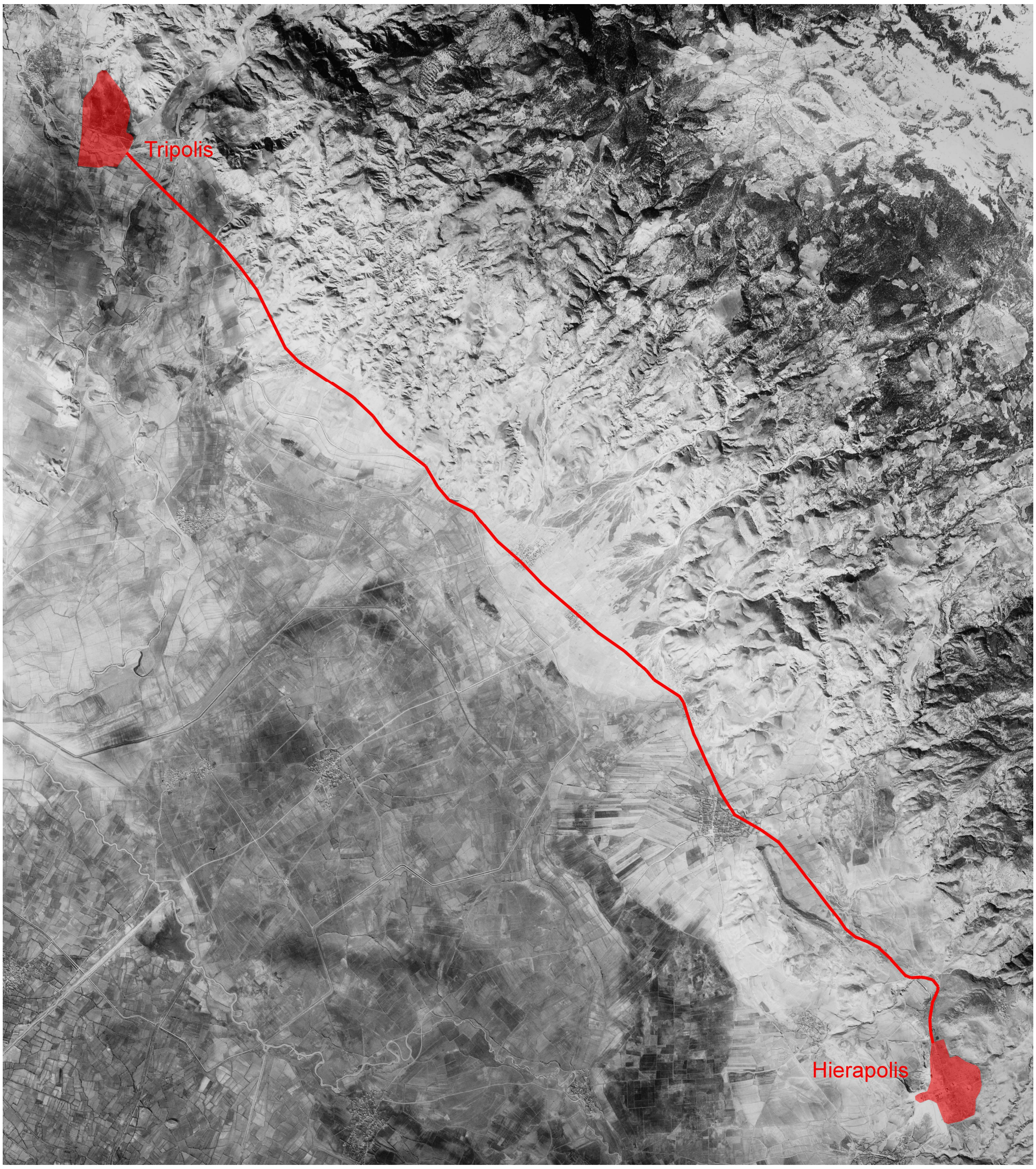

Fig. 10 - The road from Hierapolis to Tripolis in the west side of the Lykos valley, highlighted on a Corona KH-4A image of 1968.

Finally, the later phases of the settlement in the territory have also been documented, thanks to the identification of some abandoned villages of the Turkish period, with stone houses that are poorly preserved on the ground but easily identifiable from the analysis of satellite images (see below Figs. 14-15).

G.S.

Methodologies of analysis and processing of satellite images for archaeological purpose

Among the research activities of the Hierapolis of Phrygia Survey Project some processing was carried out on different satellite images, panchromatic and multispectral, acquired from Ikonos and QuickBird satellite. In particular, work was oriented in two directions: on the one side, we proceeded to elaborate the multispectral bands and to the production of high resolution colour images from the fusion with panchromatic images through various algorithm of pan-sharpening; on the other side, the geo-referencing and orthorectification of panchromatic images for cartographic purposes were carried out.

The multispectral processing of the images and the subsequent analysis of data from the near infra-red and from the bands of the visible spectrum, were taken up in successive steps: the first phase of the work is consisted in the fusion of the different bands forming the dataset of a raw satellite image. One must bear in mind, in this matter, that the sensors of commercial satellites QuickBird and Ikonos acquire at the same time the same image in two different geometric resolutions: the panchromatic ones can reach a resolution at nadir of about 0.60 and 0.80 m, while the multispectral a resolution between 2.40 and 3.20 m. The acquisition in multispectral mode for this type of satellites is in turn subdivided in four bands of the spectrum: red, green, blue (bands of the spectrum visible to the naked eye) and near infra-red (NIR - spectrum invisible to the naked eye). The images different geometric resolution does not allow their direct overlay, unless an appropriate breakdown of the pixels is carried out, and a re-sampling through several algorithms: the most well-known, and most functional for images analysis for archaeological purpose, are those of Zhang (ZHANG 2004), implemented in the PCI Geomatica software, and of Gram-Schmiedt. With these algorithms, it is possible to obtain high resolution images (0.70 and 1 m) in the four bands acquired by QuickBird and Ikonos sensors.

Fig. 11 - Pan-sharpened image (with colour normalized RGB, bands 4-3-2) of the north-eastern sector of Hierapolis: traces and remains of the Byzantine city walls are visible.

The orderly overlaying of the single bands thus allows to visualize the image in true colours or in false colour, highlighting each time the different types of anomalies: for example, the use of red and near infra-red bands resulted being the most suitable to spot those anomalies that are an outcome of vegetation growth. In fact, in the visible spectrum the red wavelength is very sensitive to the energy absorbed by chlorophyll during photosynthesis, while in the near infra-red the energy released by the internal structure of the leaves is highlighted. These data are analyzed by the dedicated software that elaborate, through some algorithms, the growth rate of vegetation in a defined area (Fig. 11); these are interpreted in order to acquire new data on the potential presence of interred structures that have affected vegetation growth. This was, for example, the case with the archaeological evidence recognized in the QuickBird image processed in false colour (bands 4-3-1), in which it is possible to observe an anomaly in vegetation growth in correspondence of the end of a densely cultivated area: during the direct survey on the ground several blocks of travertine, fragmentary tiles and pottery were found (Fig. 12). On the basis of these finds it was possible to associate this anomaly to the presence of a possible ancient farmhouse, of which only partial remains can nowadays be distinguished.

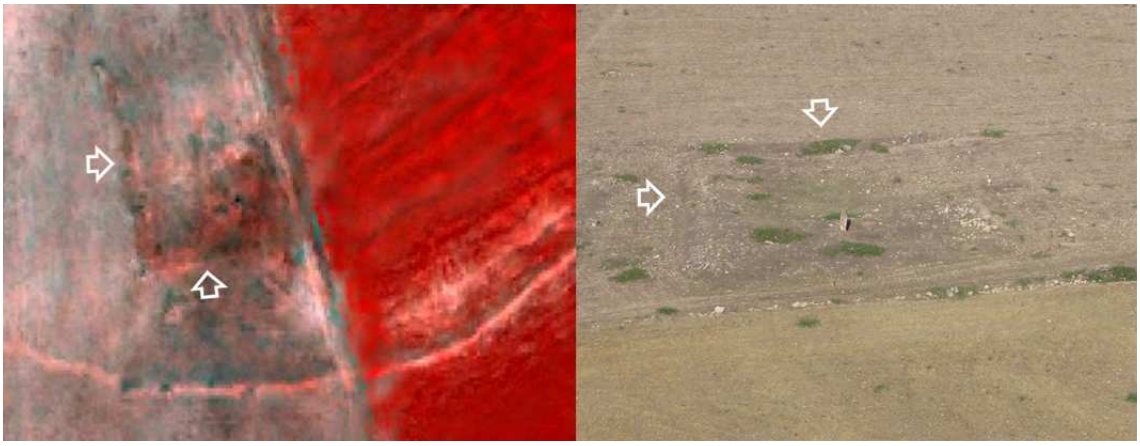

Fig. 12 - Traces of an ancient farmhouse visible in a pan-sharpened image of QuickBird (bands 4-3-1); on surface are visible only fragments of bricks, pottery and blocks, and some semi-emerging structures.

The actual value of data acquired from space, therefore, as well as being tied to the archaeologist's capability of reading and interpretation, is also strictly connected to a good processing of the image through the use of sophisticated enhancement techniques, and is in any case always depending on on-field verification. The data acquired through satellite images processing and analysis, having been validated by ground survey, are systematically directed in the Hierapolis GIS, contributing to the enrichment of the archaeological map of the city's territory.

The geo-referencing and orthorectification of satellite images related to Hierapolis' urban area and territory were necessary due to the scarce availability of updated maps and of an adequate level of detail for field work. To solve this problem, we proceeded with the creation of space-maps and we experimented with the design of cartography specifically aimed at archaeological research obtained from satellite images. A series of control points were located on the ground to obtain a high degree of accuracy, pivotal for the elimination of distortions typical of satellite image capture, but also, in general, of images taken from some altitude (TOUTIN 2004); so, it was necessary to "link" the satellite image to the ground by means of real coordinates, surveyed with high precision topographic instruments (differential GPS equipped with radio modem for real time rectification of the coordinates). To obtain a good orthorectification it is also necessary to take into consideration the satellite's position (and, consequently, of the sensor mounted on it) in relation to Earth, and its attitude; these parameters, commonly named RPC (Rational Polynomial Coefficients), vary from image to image, and are released in association with it as metadata. By means of the Ground Control Points surveyed on the ground, the RPC and the terrain models obtained through vectorization of contour lines photoprojected in the 1970s by the General Command of Mapping of Turkey, and elaborating data from SRTM and from a stereo-pair acquired in NIR by the ASTER sensor, we proceeded with the geometric correction of satellite images for the creation of space-maps to be used as basemaps during archaeological surveys and for the placement of archaeological evidence identified in the GIS of Hierapolis and its territory.

A stereo-pair from Ikonos satellite was acquired for the urban area of Hierapolis e for the part of its territory included between the villages of Yeniköy e Küçükdereköy, about 2 km south-east of the ancient town, in which there is a concentration of numerous archaeological remains from various periods. For the second area, for which no detailed cartography was available, the creation of a cartography aimed at archaeological research and derived from satellite images was tried out; the GCPs surveyed on the ground were useful, other than for the orthorectification of the image from which the map thematisms were extracted, also to create a high resolution three-dimensional model of the terrain. The equivalent points identified in both the stereoscopic images represented the starting point for their processing to obtain an anaglyph, very useful to highlight the data from the analysis of micro-relief. At the same time, beginning from the model obtained setting up the two stereoscopic images, we also proceeded with the extraction a Digital Surface Model (DSM) that was then used to extract the contour lines with intervals of 1 m (BAIOCCHI et al. 2005, EISENBEISS et al. 2004); nevertheless, in this phase we experimented on the limit of the algorithms in the shaded areas, in which the 3D surface model resulted very disturbed and not very useful for the reconstruction of the terrain’s morphology, requiring many interpolations.

G.DG.

From traditional photogrammetry to fast-mapping from high resolution satellite images

Photogrammetry has traditionally provided a means of generating three-dimensional spatial data to represent terrain surfaces, which complements traditional ground-based surveying methods. Although techniques such as airborne laser scanning and synthetic aperture radar have developed, photogrammetry remains the primary method of generating topographic maps. One important advantage of photogrammetry is the flexibility of scale that allows application to images acquired from ground, air and space. Indeed, a new generation of high resolution satellite sensors is likely to further increase the potential of its applications. Despite many advantages, there have been several problems using traditional methods of photogrammetry; most significantly, there was the requirement to use an expensive and complex photogrammetric stereoplotter. This made the measurement process slow and generally requiring the skills of an experienced operator, particularly if results of the highest accuracy were to be obtained. Rapid developments in computing hardware and software have allowed the science of photogrammetry to develop rapidly during the last ten years; these developments have radically eased many of the problems and limitations associated with traditional analogue instruments. Satellite images, oblique aerial photography and ground-based images can be used, in addition to the more traditional vertical aerial perspective.

During the last two decades the level of specialization in the development of cartographies for archaeological purposes, aimed at compensating for the technical incompatibilities caused by the different uses for which commercial maps were made, has progressively increased. In their most frequent use, in fact, archaeological maps are assembled by importing detailed archaeological elements, almost always resulting from direct observation and survey, on a generic topographic base, which usually lacks upgrades and is often found in an inadequate scale. This results in a composite product that shows deep deficiencies since the archaeological data is inserted in an often too approximate topographic context. Consequently, due to diverse and peculiar requirements, the necessity for a specifically aimed photogrammetry emerged, in which the possibility is given to choose both the scale to be adopted for the represented objects and which elements need to be emphasized or require more accuracy in the details. One of the most neglected aspects in commercial cartography is the rendering of altimetry, only represented as a tendency; on the contrary, a correct rendering of the contour lines is fundamental for the reading of the topographic context and for the graphic representation of the archaeological elements that must be, as much as possible, real and never symbolic. When the aerophotographic base allows it, that is when the scale of the available stereoscopic images is large enough, the cartography obtained can boast remarkable detail: in practice, this means topographic maps 1:1,000 and 1:2,000 in scale, in which the contour lines can be plotted with an interval up to 50 cm. It is evident how the cartographies aimed to archaeological research will result more easily achievable if they are produced by or in presence of an archaeologist, who has direct knowledge of the requirements for representation and is familiar with photographic interpretation of landscape morphology and of those traces referable to interred archaeological remains.

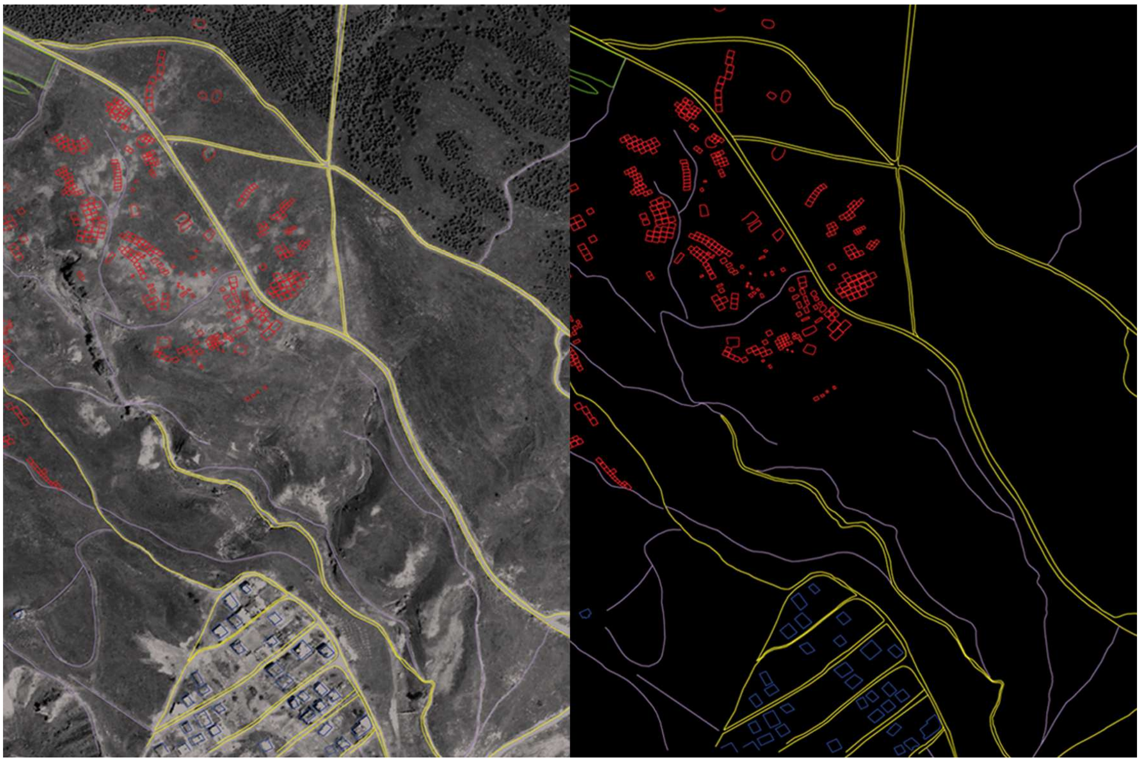

Fig. 13 - An example of the cartography during restitution: in yellow are modern roads, in violet the paths, in blue the modern houses of Yeniköy and in red the archaeological evidences (particularly, traces of an old Turkish village, now destroyed).

Each represented element will have its own alphanumeric and colour code according to the information layer to which it belongs: Planimetry, Hydrology, Geomorphology, Vegetation, Administration Limits and toponomy, Reference Points and Topographic Landmarks, Archaeology. The latter layer, on the basis of encoding layers developed in the Ancient Topography and

Photogrammetry Laboratory of the University of Salento, is further divided in 9 functional areas that allow a precise identification of all the represented objects (PICCARRETA, CERAUDO 2000).
This branch of research can be connected, conceptually and methodologically, to that of the possibilities of cartography production and update offered by high resolution satellites, in particular in study contexts where there is no adequate cartography available and it is difficult or impossible to retrieve stereoscopic aerophotographic coverage (HOLLAND, MARSHALL 2003; GIANINETTO, SCAIONI 2004; JACOBSEN 2006). From the satellite images available at the moment, after an accurate orthorectification, map thematisms can be extracted for the production and upgrading of maps in scales included between 1:25,000 and 1:5,000, which can thus be specifically aimed for archaeological research; furthermore, the stereo pairs acquired from satellites such as Ikonos, EROS A1, and B1, from the ASTER sensor, and now also from WorldView-1, allow the creation of high resolution DEMs, useful for image orthorectification, but also for a detailed documentation of the territories' orography. In the Hierapolis of Phrygia Survey Project such methodology was applied to a limited portion (c. 8 km^2) of the territory located south-east of Hierapolis, between the modern villages of Yeniköy and Küçükdereköy, characterized by a concentration of archaeological evidence dating from the Hellennistic to Ottoman periods (DI GIACOMO, DITARANTO, SCARDOZZI 2008).

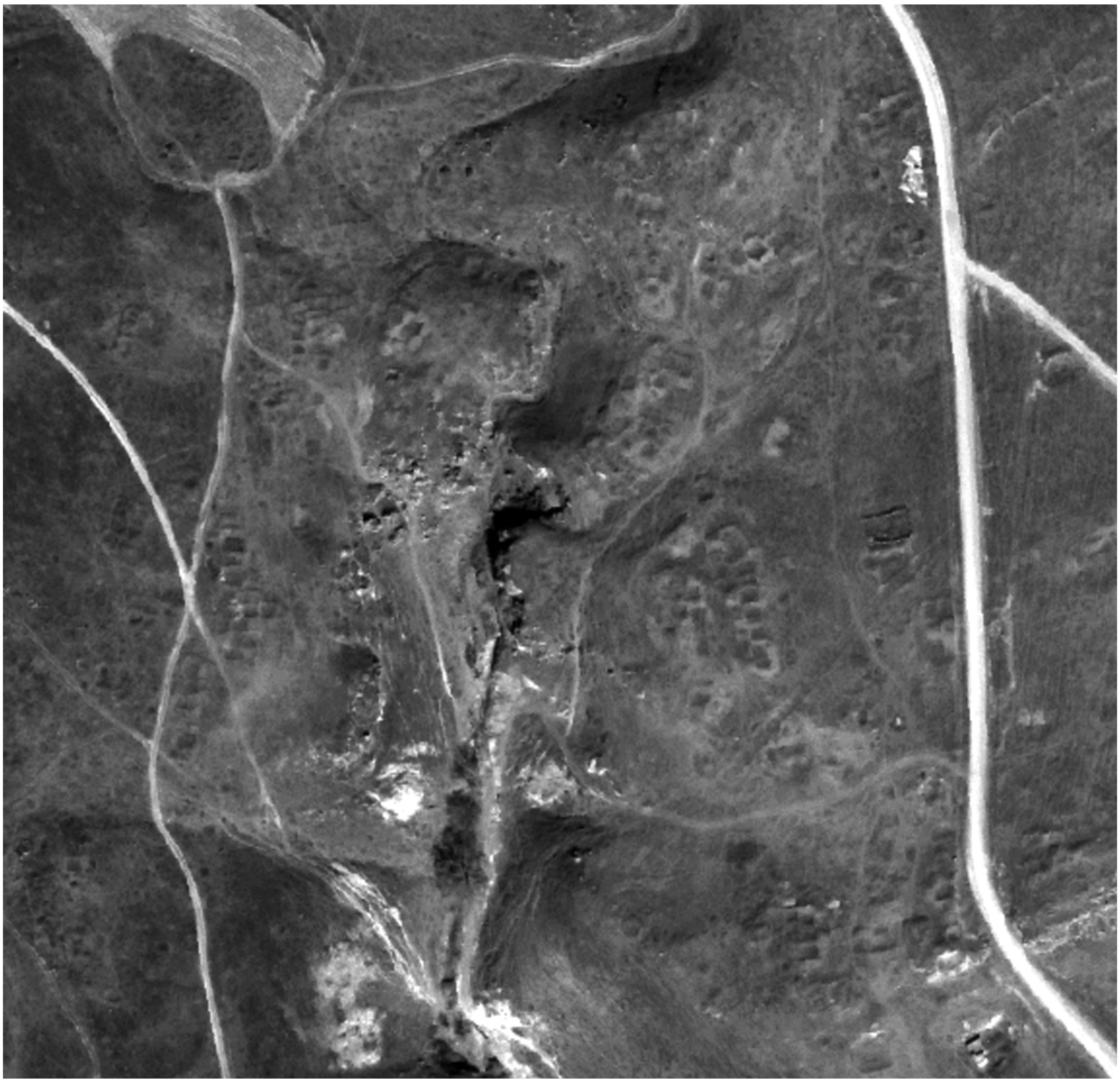

Fig. 14 - QuickBird image of 2005 that shows numerous traces of square and rectangular collapsed buildings of an abandoned Turkish village sited south of Hierapolis; they are scarcely visible on ground.

For this area, only a Turkish map 1:25,000 in scale updated in 1990s is available, absolutely inappropriate to position the single archaeological evidences surveyed; furthermore, the aerophotographic coverage of the area is not available. For this work a stereo pair captured in 2004 by satellite Ikonos (Geo-Ortho Kit Bundle) was used. The satellite panchromatic image with a smaller off-nadir angle has been orthorectified by DEMs elaborated on the SRTM and ASTER data and by GCP ant TP collected during field work with a differential GPS system. From the orthoimage many thematisms were extracted: fields, streets and country roads, modern houses and, finally, archaeological remains and traces (Fig. 13).
During the restitution phase, the most feasible, correct and detailed way to represent morphology of the territory has been researched, so that information, in particular regarding altimetry, would be legible: this aspect cannot be absolutely disregarded for the creation of a cartography aimed to archaeological research. On this subject, different methods have been compared for the creation of the contour lines: the vectorization of contours lines with 10 m interval of the Turkish cartography in

scale 1:25,000, and the extraction of contours lines with 1 and 5 m interval from the high resolution DEM extracted from the Ikonos stereo pair, and from the DEMs based on SRTM and ASTER data. The contour lines deriving from the Turkish cartography are obviously the only ones resulting from real measurements (aero-photogrammetry restitution), while the others derive from an automatic process of extraction, though they come close to the real aspect of the studied territory.

Fig. 15 - The edifices of an old Turkish village found during the archaeological survey: on ground are visible rectangular and square traces like micro-relief and remains of stonewalls.

The numerical cartography we obtain is in accordance with the standard themes of cartographic production: they are set in layers and the different homogeneous elements of the map follow a logical affinity. On this base-map, all the archaeological remains detected on the ground during survey have been geo-referenced using a GPS; moreover, numerous archaeological traces were detected and geo-referenced in the new cartography thanks to the analysis of a QuickBird image (Figs. 14-15) of the study area taken in 2005 (panchromatic data and pan-sharpened real and false colours images).

I.D.

High resolution satellite images: from research to presentation of archaeological data

The Hierapolis of Phrygia Survey Project offers a point of view on the various applications of satellite images to archaeological research, highlighting the full potential of this specific search tool. In fact, the limited availability of aerial photos and up-to-date maps on an adequate scale has made it necessary

to use satellite images, at different levels, in each phase of the research: not
only during territory analysis and field work, but also as space-maps during research and for the presentation of data, and as one of the base-maps of GIS, viewed alone or in combination with other cartographic levels included in the system.

All these different uses have been made possible by the wide availability of satellite images for the territory of Hierapolis in the archives of the companies owners of satellite platforms or specially commissioned. These images are at different levels of resolution: very high (QuickBird and Ikonos images) or less detailed but very important for the historical data showed (Corona and Hexagon images). For a contextualization of Hierapolis in its territory and a study of the latter to a lower detail scale, satellite images, with a middle-low spatial resolution between 15 and 30 m are also used: SPOT-1 images, Landsat 4 and 5 TM and Landsat 7 ETM+ images, and ASTER images (SCARDOZZI 2008a).

Fig. 16 - The aqueducts of Hierapolis on a DEM draped with a QuickBird image of 2005 from Google Earth: in red the preserved routes and in pink the assumed ones.

Research in the territory of Hierapolis has indeed benefited from the fact that since March 2006 it has been nearly completely covered by pan-sharpened QuickBird images in real colour visible in Google Earth; the images, despite being compressed as part of their visualisation on the Internet, maintain a high geometric resolution (about 0.70 m), which enables the video-exploration of the entire area before the field work: the images of the areas of interest are downloaded, geo-referenced and used during survey. The satellite images visible on Google Earth, integrated with those that were purchased, therefore provide a complete coverage of the territory included in the research project, the western side of the Lykos valley and the plateau North of Hierapolis. When during the survey particularly interesting areas are located, sections of the original scenes are then purchased: so the processing of the panchromatic and multispectral data is possible.

To fully exploit the enormous amount of information contained in the satellite images experiments were carried out for the visualization of images in 3D in order to associate archaeological traces to the morphology of the ground. Thanks to the low-resolution DEM used in Google Earth, which makes it possible to appreciate the morphology of the terrain, it was possible to view 3D satellite images of the areas covered by the research; in those cases where the QuickBird images purchased as part of the project were not present in Google Earth, its DEM was still used to visualise them in 3D, using the image overlay function of the software. Exploiting the possibility that allows users to insert additional data in Google Earth, during the research in Hierapolis the data provided on-line by the server has been integrated with the positioning of the discoveries and the relative metadata recorded in the survey.

Therefore, the QuickBird images visible in Google Earth allowed a simple visualization in both two and three dimensions, highly useful in the rendering phase and the presentation of results of archaeological research. Using other softwares for data treatment, it was also possible to import in Google Earth waypoints from the GPS receivers used in the field work; in the case, for example, of traces of linear phenomena, such as roads or aqueducts, it was possible to obtain a rapid and relatively precise reconstruction of the pattern of the road or water distribution networks, visualising their routes with both static images and flight simulations (Fig. 16).

The integration of data acquired through the use of GPS to the yield of three-dimensional satellite images allows, in the case of roads or the aqueducts above mentioned, to undertake a number of assumptions and to test the feasibility of the routes, which take into account the different factors related to land morphology, such as quotas, slopes and distances. Also the possibility to obtain measurements that take into account the real shape of the land must not be underestimated in the interpretation of general linear phenomena.

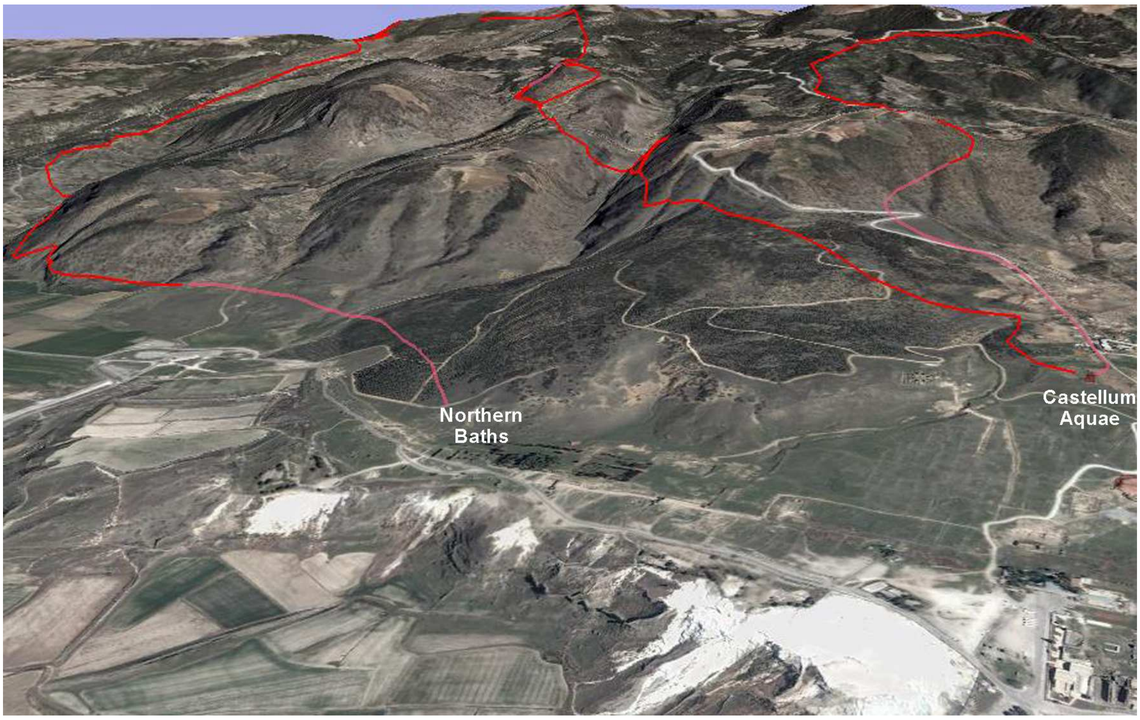

Fig. 17 - High resolution DEM extracted from an Ikonos stereo pair and draped with a pan-sharpened image in real colours (bands 3-2-1) of the same satellite.

Again with a view to a more effective analysis, management and presentation of the results of the research, other DEMs were processed, at various resolutions, low for larger areas and high for more detailed sectors, based on GTOPO30 and SRTM data, ASTER and Ikonos stereo pairs and differential GPS measurements (Fig. 17). Satellite images were draped on the DEMs and the archaeological evidences considered in each case were positioned on them. The possibility to show the territory in its real morphology allowed to make several assumptions based on the close relationship existing between morphology and population or, more generally, territory exploitation. Apart from the levels seen so far, collection, processing and presentation of data, satellite images have proved themselves very useful in the additional phase of the disclosure of data, used as one of the bases of the webGIS (http://antares.ibam.cnr.it/atlante-hierapolis) for the monuments and necropolises of Hierapolis in Phrygia (CASTRIANNI et al. 2008).

Fig. 18 - Example of a query in the web Atlas for the monuments and necropolises of Hierapolis.

The organisation in layers enables navigation on the 2005 QuickBird satellite image (suitably “lightened” for web exploration) and – should the user require it – on the archaeological map superimposed on that image (Fig. 18). The satellite image, which provides a fairly up-to-date and detailed overhead view of the city and its surroundings (with a ground resolution of about 0.70 m), in the future may be replaced with a more recent image or accompanied by other layers, such us further satellite images acquired in different years and/or by different satellites. The layer with the archaeological information is linked to a database that allows the users to make simple or complex queries, integrating spatial and chronological data. The final users is thus provided with cartographic data, the satellite image and historic and archaeological data, for a highly dynamic approach to the knowledge of the ancient city.

L.C.

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