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Orthophoto generation using IKONOS imagery and high-resolution DEM: a case study on volcanic hazard monitoring of Nisyros Island (Greece)

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Abstract

Georeferenced high-resolution satellite images can be used for acquisition of topographic information, navigation and visualisation for various environmental studies. The present study is part of the multidisciplinary EU project GEOWARN related to monitoring, warning and emergency planning for volcanic hazards in the island of Nisyros, Greece. Here, the main aim was the orthorectification of a 1-m resolution pan-sharpened IKONOS Geo image of Nisyros island. For the orthorectification, a digital elevation model (DEM) with a cell size of 2 m and an RMS accuracy of ca. 3.5 m was used, as well as 38 selected ground control points (GCPs) measured with differential GPS. An object-to-pixel space transformation using the ground control points was computed using two different models, a relief-corrected affine transformation and the polynomial mapping functions of Kratky. These transformations were used for orthorectification and the orthophoto accuracy was evaluated using GCPs as check points. Postprocessing for radiometric improvement of the orthophotos was applied. The orthophoto and the DEM served as basic tools for subsequent base mapping and visualisation.
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Keywords: IKONOS; orthophoto; DEM; differential GPS; mapping; multimedia information system; natural hazards; volcano

1. Introduction

The islands of Nisyros, Yali, Kos, Santorini, Milos, Poros, Aegina and the peninsula of Methana constitute the Hellenic Volcanic Island Arc (HVA). The eastern sector of the HVA, including the islands of Kos, Yali and Nisyros, seems to be geodynamically very active since it comprises the largest volumes of volcanic materials and is at present a region of high tectonic activity.

Active volcanoes represent severe natural hazards, especially for populated regions. These hazards often occur as combinations of earthquakes, gas explosions

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and hydrothermal eruptions, volcanic eruptions, landslides, mudflows, tsunamis, etc. Because of the above aspects, the EU research project GEOWARN has been established. The objectives of this scientific study are to conduct an integrated informative, volcanological, geophysical and geochemical project to assess volcanic and seismic hazards related to the most active part of the Eastern Mediterranean by the help of a GIS database, as well as by an integrated geo-spatial multimedia system of the region (www.geowarn.org). Fig. 1 shows an overview of the data processing workflow within the GEOWARN system. Eight institutions collaborate in this project and a large amount of heterogeneous information has to be produced and treated, like: graphical and numerical geo-spatial data, visualisations, satellite images and derived products, real-time monitoring of ground movements (differential GPS (DGPS) and differential SAR interferometry), seismic activity, changes in fumarolic gases and high hydrothermal waters (see also www.geowarn.org). The Remote Sensing data involved include IKONOS, thermal images from LANDSAT 7 TM and ETM+, ASTER and differential interferometric ERS SAR images for deformation analysis.

One of the basic features of the GEOWARN project was the creation of an updated topographic map, since the newest edition at the scale of 1:5000 dates from 1982/1983: it is a raw, single-colour stereophotogrammetric compilation without significant cartographic redesign. The resulting map of Nisyros Island processed in the framework of GEOWARN is at the scale of 1:10,000 and contains all

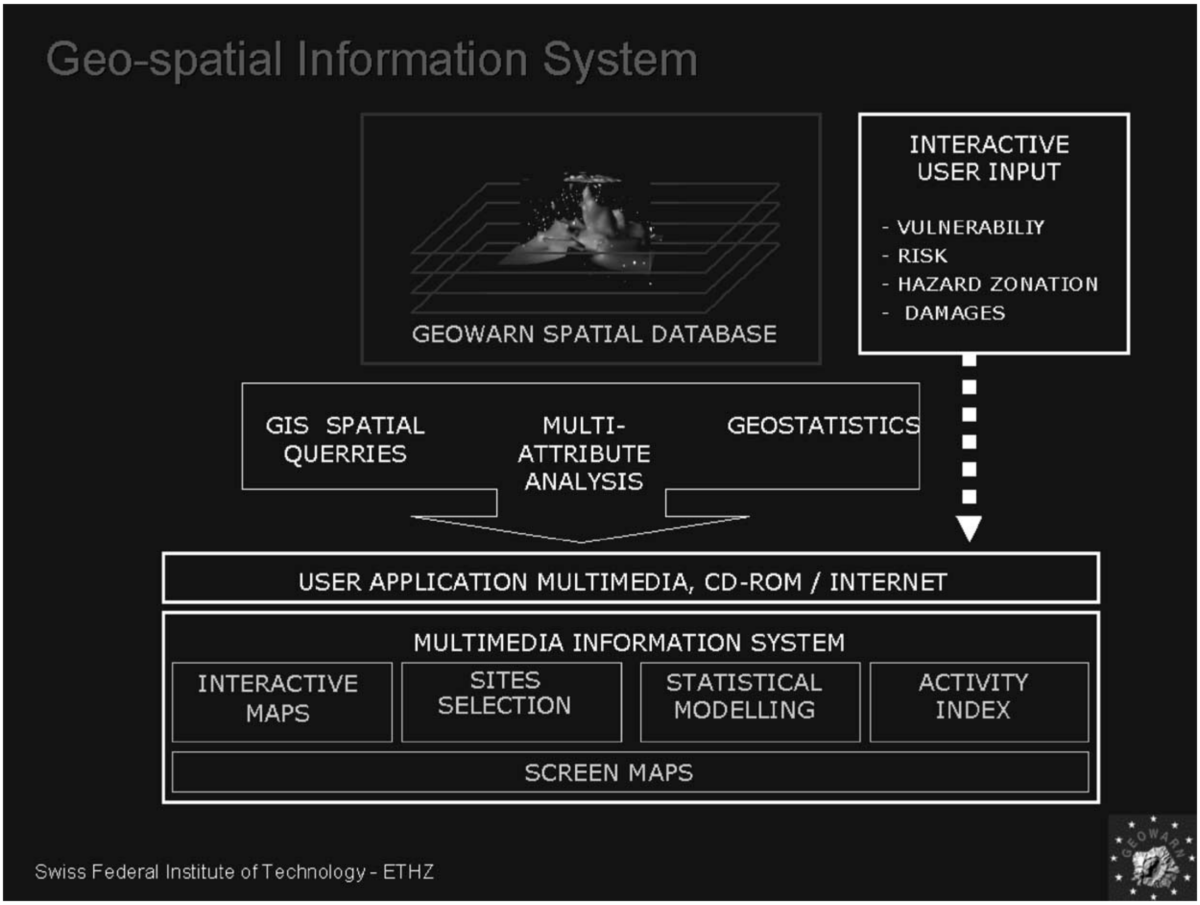

Fig. 1. GEOWARN data processing workflow.

the updated topographic data classified in categories such as roads (i.e. primary, secondary, trail path), buildings (i.e. houses, churches, ruins) and land use (i.e. forests, barren land, cultivated areas, rocks, villages). The map will serve as a new topographic map for local inhabitants, tourists and the public administration. In Nisyros, the latter will mainly use it for emergency planning of Nisyros volcano. A georeferenced high-resolution satellite image is, therefore, a useful tool not only for the updating of the classical topographical map but also for supporting high-accuracy orthophoto mapping. Due to strategic reasons, aerial images of the area are not available for civilians. The easily accessible, area-wide IKONOS images were at the time the only reliable alternative. The aim of the present study was the orthorectification of a pan-sharpened IKONOS Geo image with 1-m resolution of Nisyros Island (Greece). For the orthorectification, a digital elevation model (DEM) with a cell size of 2 m was used. Thirty-eight selected ground control points (GCPs) were determined with high accuracy using differential GPS. The final orthorectified image was based on the Hellenic Geodetic Reference System (HGRS'87).

Subsequently, orthophotos can be used as navigational tools, for visualisation and as parts of multimedia information systems. Such tools are of essential value for emergency planning, crisis management and change-detection procedures in devastated areas due to any natural disasters (floods, forest fires, earthquake devastation, volcanic eruption, etc.), as well as for all areas, especially nonaccessible ones, without proper maps. Schiewe (2001) and Meinel and Reder (2001) report about first experiences with IKONOS images for topographic mapping and map updating and postulate their applicability at scales of 1:10,000 and smaller.

2. Image data and preprocessing

2.1. Image data

The IKONOS satellite (launched in September 1999) is the world's first commercial satellite offering high-resolution imagery. IKONOS data include 1-m panchromatic, 4-m multispectral images in the VNIR and 1-m pan-sharpened multispectral images involving three out of the four available spectral channels (B, G, R and NIR). IKONOS is agile pointing at any azimuth and with an elevation typically larger than 45°. Data are collected at 11 bit; however, in reality, a much smaller range than 2048 grey values is covered in each image. The Geo product is the cheapest one and is geometrically corrected using bicubic interpolation to a cartographic projection and a reference ellipsoid, without use of GCPs or DEM for the geocoding. More details on IKONOS can be found at www.spaceimaging.com.

Pan-sharpened Geo images (PAN-MSI) of Nisyros Island were ordered from Space Imaging Europe, including the G, R and NIR channels as a false colour image. They covered an area of ca. 9.5×9.7 km centered at 36.59°N and 27.16°E. They were preprocessed by modulation transfer function compensation (MTFC), but no dynamic range adjustment (DRA). The first image had about 10% cloud cover, mainly at the western and central parts of the island (Fig. 2). A second image with more cloud coverage (ca. 15%) was used to check a possible automated extraction of a DEM via image matching, a topic which will not be dealt in detail in this paper. The main parameters of the images are shown in Table 1. As it can be seen, image 1, which was used orthorectification, had almost identical azimuth for sensor and sun, thus, leading to the favourable condition that shadows almost coincide with occluded areas, but without leading to saturation, due to lack of strongly reflecting surfaces vertical to the viewing direction. The elevation, although not optimal, was quite good, and the atmospheric conditions were also quite fair with lack of haze. The Geo images were in UTM projection (zone 35) with WGS'84 datum and a nominal accuracy (90% CE) of 50 m. This error does not include errors caused by relief, nor the fact that the ellipsoid used for geocoding of Geo images refers to an arbitrary mean height (so-called inflated ellipsoid).

The nearly circular volcanic island Nisyros is mainly rural. The ground morphology begins from the sea level and forms a caldera rim at an altitude of about 200–300 m, while the overall relief varies between sea level and about 700 m. Cultural features, such as villages and tared roads, are relatively scarce. Vegetation is not very dense and includes both trees and bushes.

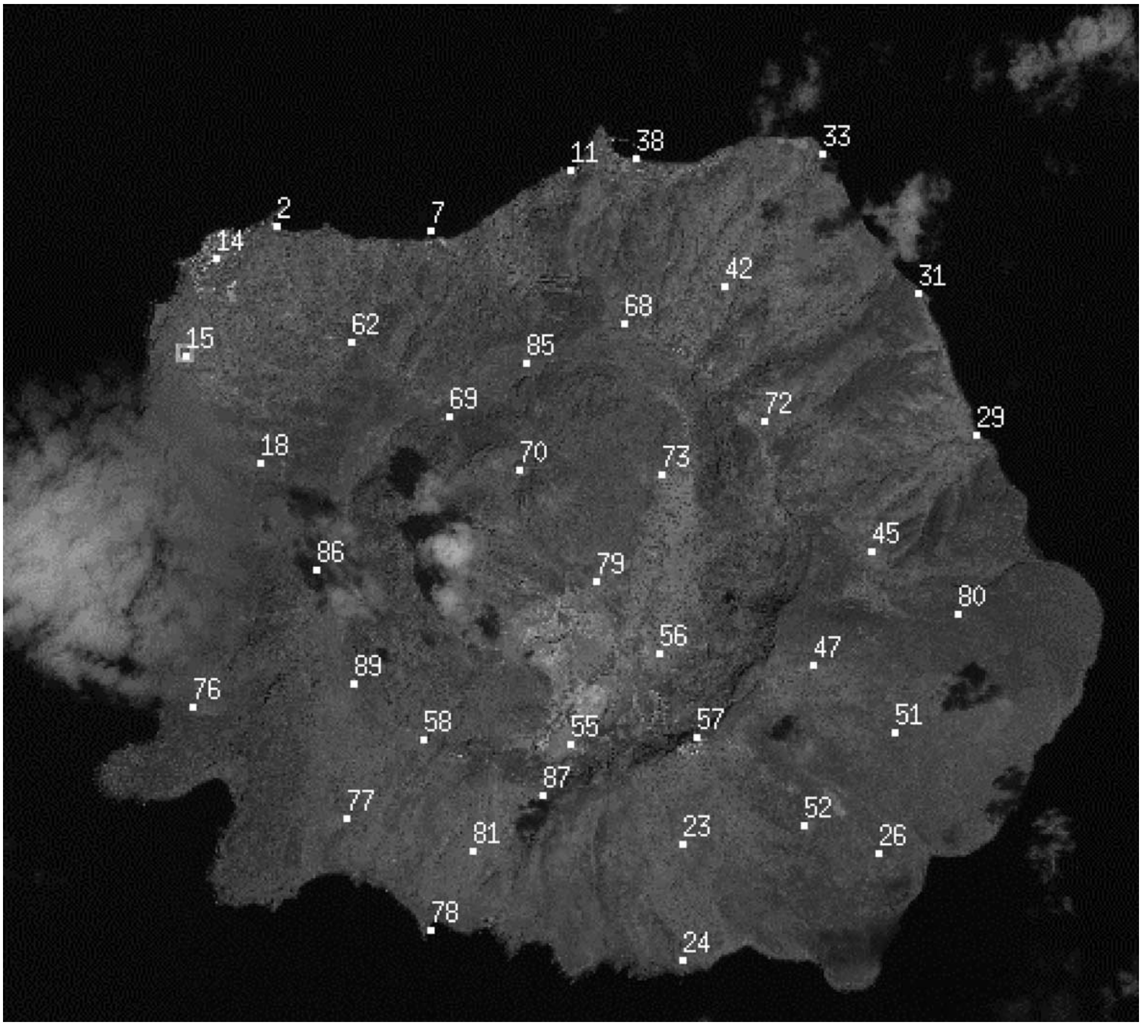

Fig. 2. IKONOS image of Nisyros Island with selected ground control points for orthorectification.

2.2. Image quality and preprocessing

The original 11-bit images had min/max values: NIR 0/2008, R 0/1866, G 87/1838. They were reduced linearly from (min, max) of the three RGB channels to 0,255 and split to one file per channel with the IDL software. This was necessary for further processing with own software. The reduction to 0,255 was for all three channels simultaneously, not for each separately, to avoid changing the relations between the channels, i.e. the same offset and gain were used for all three transformations. The R and NIR channels had visually better quality and showed more details, especially NIR in vegetation. The effective grey value ranges of the 8-bit images (excluding a dark peak due to sea water) were 30 (30–60), 40 (20–60) and 60

Table 1
Acquisition parameters of used IKONOS Geo images

Image acquisition parameters	Image 1	Image 2
Acquisition date/ local time	8 April 2000/ 10:35 am	28 March 2000/ 10:34 am
Sensor elevation (°)	73.5	72.7
Sensor azimuth (°)	134.9	72.1
Sun elevation (°)	53.4	49.3
Sun azimuth (°)	136.6	138.7

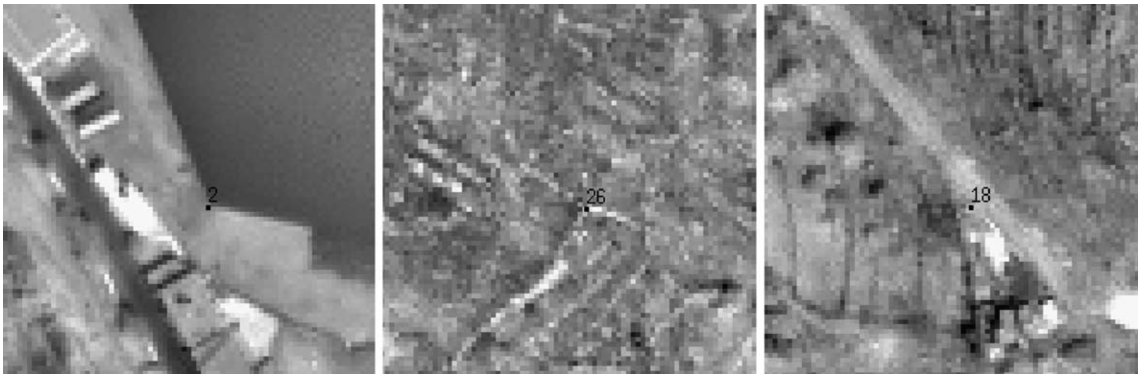

Fig. 3. Some of the used GCPs with variable image localisation quality: good (left), medium (middle), poor (right).

(40–100) for G, R and NIR, respectively. NIR had the highest contrast and was brighter. In NIR, vegetation is brighter than in R and G and more difficult to distinguish from dirt roads compared to the other two channels. R was best to distinguish texture in vegetation. Buildings were similar in all channels, with shadows being slightly darker and more pronounced in NIR. Further preprocessing could be applied, e.g. to reduce noise and enhance contrast, but it was decided to apply such procedures directly to the orthophotos.

3. GCP determination using DGPS measurements

Thirty-eight ground control points (GCPs) were collected using DGPS measurements during 2001. Two geodetic GPS receivers were used (WILD SR 299). The coordinates of the GCPs were calculated from ties to the permanent GPS stations of the Nisyros GPS network (Lagios et al., 2001). The Nisyros GPS network refers to a pillar at the NE part of Kos Island, about 33 km to the NE of Nisyros. That pillar (no. 182) belongs to the Hellenic First Order Geodetic Network, EGSA'87 (the Hellenic projection system using the GRS'80 ellipsoid), and has coordinates X = 792,708.63 m, Y = 4,087,832.75 m and height = 32.320 m.

The processing and adjustment of the GPS observations were made using the SKI Pro software of Leica, which was adequate as an analysis tool due to (i) the small distances of the measured baselines (Dixon, 1991), and (ii) the very high rate (5 s) of sampling and long recording time (45–60 min) (Lagios et al., 1998; Lagios, 2000; Ganas et al., 2002). The calculated adjustment error was 1–3 mm for the horizontal and 2–5 mm for the vertical coordinates.

The IKONOS pixels, where the GCPs lie on, were identified in situ by the use of a laptop and the ERDAS software during the DGPS measurement procedure. The position of the GPS measurements is indicated on the IKONOS image (Fig. 2), covering an elevation range between 0 and 400 m. GCPs failed to be identified at some important parts of Nisyros, like along some parts of the coastline and the caldera rim. The selection of GCPs was quite difficult and time-consuming, since well-defined man-made objects were missing in many island parts. The pixel coordinate accuracy is estimated at 0.5–2 pixels, with a mean value of 1 pixel. Fig. 3 shows some typical examples of GCPs and their definition quality. Some used points, like building corners and corners of harbour platforms, although optically well-defined, include errors due to the sensor azimuth, e.g. the ground building corner was occluded and thus actually the building roof was measured.

4. Generation of high-resolution DEM from topographic maps 1:5000

4.1. General

The use of a DEM is important for any environmental study of a region.

- It represents an important component (3D terrain representation) for maps and GIS databases and serves as a base for thematic applications (geologic, tectonic), orthophoto generation, etc.

- It serves as a base for production of a great variety of maps (3D maps, slope-aspect maps, etc.)

A high-resolution DEM had to be produced, since there was not any other DEM available for this island, particularly with such a high resolution of 2 m. Like for the other map elements (see Section 4.2.1.1), a large number of various topographic data (contour lines, elevation points and drainage network) from topographic maps 1:5000 of the area was compiled as input data for the DEM generation. Contour lines, trigonometrical points, spot heights, additional elevation points, drainage network) were compiled in vector format and structured in layers in a common GIS (ArcInfo). The digital elevation model was produced with a 2-m grid cell resolution.

4.2. Methodology

The applied methodology for obtaining a DEM depends on numerous parameters, like the type of the data (contours, points, drainage network, etc.), the quality and the density of the data, relating to the morphology of the study area, as well as the use of the DEM. The result (DEM) depends on the parameters of the applied algorithm, the dimension of the DEM (i.e. the pixel size of the regular grid to be interpolated), the scale of the map in which the DEM is represented, etc. (Vassilopoulou, 1999, 2001; Vassilopoulou and Hurni, 2001).

The basic input data for the production of the DEM were contours with a good density (10-m contour interval, as well as 4 or 2 m in some specific regions), together with elevation points and drainage network. Having then this kind of data available, the Topogrid algorithm of Arc/Info version 8.2 was able to generate the proper grid of elevation (ESRI, 1997; Vassilopoulou, 1999). Before the application of the Topogrid algorithm, the data needed to be preprocessed.

4.2.1. Data preprocessing

Arc/Info 8.02, as well as Arc/View 3.2 software, were used for the topographic and morphological data processing. All topographic data were categorised into geographical units, thematic layers (coverages) of lines, polygons and points. The data preprocessing, however, may be divided into the following stages.

4.2.1.1. Data input and layer compilation. The topography of Nisyros Island, in the form of 1:5000 scale paper maps of the Hellenic Military Geographical Service (1982/1983), was scanned using an Optronics 5040 drum scanner (and laser recorder) at 254-dpi resolution and then georeferenced based on the Hellenic Geodetic Reference System 1987. The axial and circumferential repeatability accuracy of ± 5 μm of the scanner (given by the company) was actually over-dimensioned for this task, since the main distortions were due to the paper. The digitisation of the topographic and morphological data, like contour lines, elevation points and drainage network, was based on those files. Their digitisation was carried out on-screen by the use of ArcScan (Arc/Info module). It was found that the RMS value resulting from the georeferencing process was less than 0.6 m.

Thematic layers (coverages) were produced according to the following categories:

	Topographic data of Nisyros	Morphological data of Nisyros
Lines	contour lines 10 m, but other contour line level was also taken in specific regions (5 m, partially 4 and 2 m)	drainage network
Polygons	the outer boundary of the interpolated grid (an area encompassing 200-m marine area around the island)	
Points	• trigonometrical points • spot heights	

4.2.1.2. Conversion of coordinates in map projection system. All the data were georeferenced based on the Hellenic Geodetic Reference System 1987 (HGRS'87). The parameters of HGRS'87 are as in the following:

Projection: TRANSVERSE
$dx = -199.87$, $dy = 74.79$, $dz = 246.62$
Spheroid: GRS'80
Scale Factor at Central Meridian: 0.9996
Longitude of Central Meridian: 24 00 00
Latitude of Origin of Projection: 00 00 00

False Easting: 500,000
False Northing: 0

4.2.2. Further processing

Some of the input data needed further processing, as well as new layers had to be created, before the Topogrid algorithm could be applied:

- Correction of the orientation of the streams: all streams are included in a line cover. All arcs-streams in this cover must be oriented to point downstream.
- Addition of elevation points from the topographic maps in specific regions: besides contour lines, trigonometrical points and spot heights, more elevation points are important for the production of a DEM in specific regions like planation surfaces (flat areas with morphological slope of 0–5%), etc.
- Creation of a polygon-coverage around the coastline: this coverage is a polygon zone. The inner boundary is the coastline and the outer boundary is approximately 200 m away from the coastline in the sea. This coverage has an elevation with a value of zero.

4.2.3. Topogrid algorithm

The Topogrid algorithm is an interpolation method specifically designed for the creation of hydrologically corrected digital elevation models (DEMs) from comparatively small, but well-selected, elevation and stream coverages. It is based on the ANUDEM software developed by Hutchinson (1989).

A set of tolerances and parameters used to adjust the calculations of the interpolation and drainage enforcement process. The values of them depend on the primary input data and the sinks that are wished to be removed (ESRI, 2001).

4.2.3.1. Output and results. A high-resolution DEM in grid format was finally produced (Fig. 4), having the following characteristics:

Cell size = 2 m	
No. of rows = 4118	
No. of columns = 4575	

BOUNDARY (m)	STATISTICS (m)
X_{min} = 778,864.500	Minimum value = – 1.383
X_{max} = 788,014.500	Maximum value = 697.537
Y_{min} = 4,049,554.750	Mean = 205.520
Y_{max} = 4,057,790.750	S.D. = 135.488

To evaluate the quality of the final DEM product relating to the input data, contours were generated from the produced DEM. These contours were then compared to the initial input contour lines. It was, thus, found that the discrepancy between these contours (initial and estimated) was ranging between 0.2 and 1 m.

4.3. DEM accuracy evaluation

For a quantitative evaluation of the DEM accuracy, the GPS points were bilinearly interpolated in the DEM. The statistics of the differences of the known GPS coordinates minus the DEM-interpolated ones were: mean with sign = 2.2 m, RMS = 3.3 m, max absolute error = 10 m. The mean difference shows a substantial systematic bias. The statistics were significantly worse in the western part of the island.

Note here that the initially digitised (input) data were taken from quite old map sheets (1982/1983) which of course may represent a different picture of the topography at some specific parts of the island due to, e.g. natural morphological and seismic events or gravel mining.

5. Orthorectification

Before performing orthorectification, a relation between object and pixel space need to be established. For spaceborne linear CCD sensors, this is usually done by determining the exterior orientation, possibly also including some interior orientation parameters and orbit constraints, with the use of extended collinearity equations and GCPs. Since Space Imaging has not released the sensor model, and no rational polynomial coefficients (RPCs) were made available by Space Imaging at that time, alternative sensor models had to be used.

Two sensor models have been investigated. The first is based on the polynomial mapping functions of Kratky (1989) and employs for the transformation from

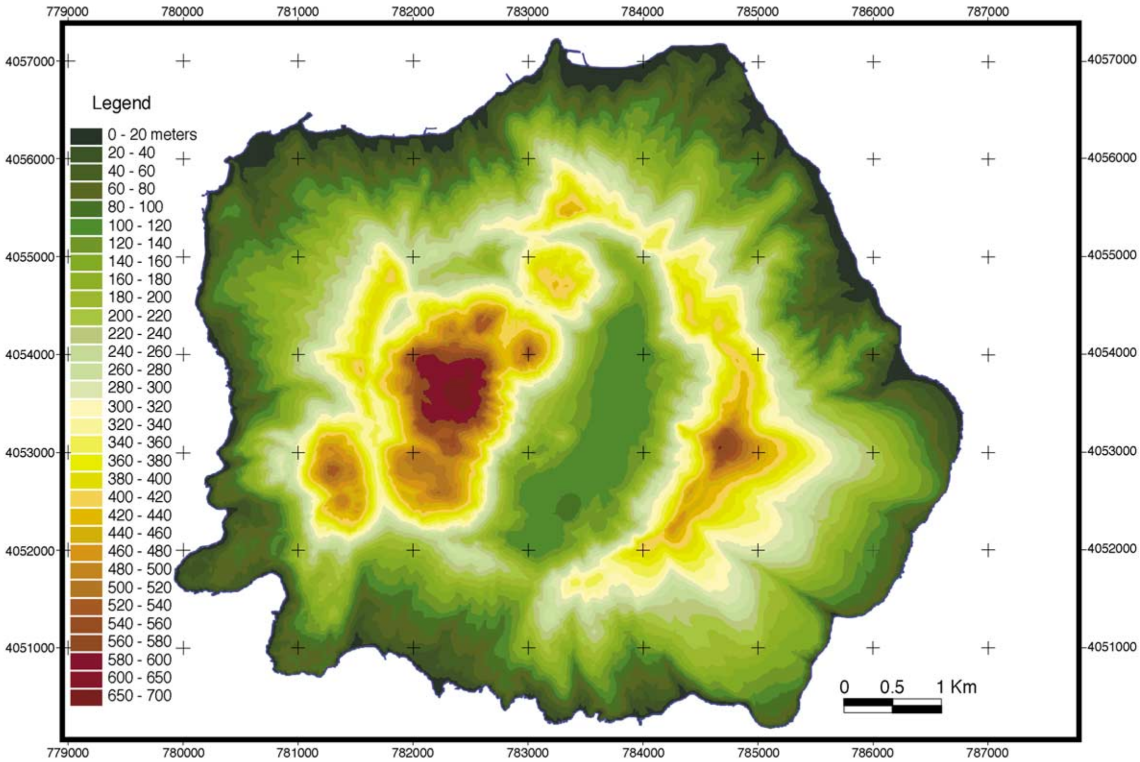

Fig. 4. The high-resolution DEM of Nisyros Island in grid format (cell size = 2 m, Datum: Hellenic Geodetic Reference System 1987, Projection: TM).

object to image space polynomials of fourth degree with 14 and 15 terms for the basic and extended forms, respectively. The extended form is supposed to model finer influences, especially quadratic terms of attitude changes of the sensor. However, depending on the number and distribution of GCPs, they may be weak or nondeterminable. This was the case with our data set, where the orthophoto with the extended model was totally distorted except from the central part which was surrounded by GCPs. Thus, in the sequel, only the basic form was used. Normally, the polynomial terms are determined after sensor orientation using a rigorous sensor model. Since this was not feasible due to the undisclosed IKONOS sensor model, the terms were estimated by least squares adjustment using GCPs. The GCPs should be dense and very well distributed covering the whole planimetric and height range, while extrapolation should be avoided. This approach had already been used for IKONOS Geo orthorectification (see Kersten et al., 2000). The second model used the relief-corrected affine transformation (for the rationale for using this model and other details, see Baltsavias et al., 2001). Firstly, the used GCP object coordinates are reduced to a reference height level (the height selection is irrelevant, but here a height of 0 m was used). Then, an affine transformation between these reduced GCPs and their pixel coordinates is estimated by least squares. A minimum of three GCPs is required, whereby their spatial distribution can be relaxed, and extrapolation does not lead to errors. This model has been used with several IKONOS Geo images for orthorectification (Baltsavias et al., 2001). The second model compared to the first one has several advantages: computation time is lower, less GCPs with not-so-stringent spatial distribution criteria are needed, and extrapolation errors do not occur. Thus, it was even anticipated that the second model would lead to higher orthophoto accuracy.

The first model was estimated once with all 38 GCPs and a second time with 28 GCPs, while the

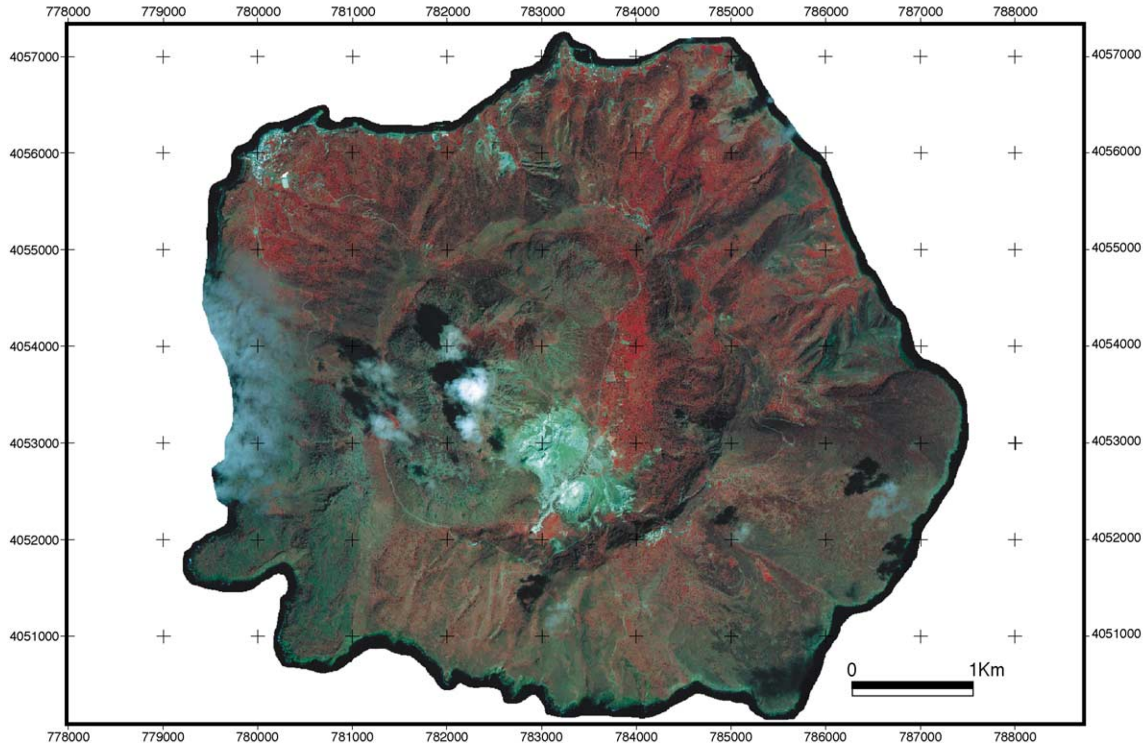

Fig. 5. The orthorectified IKONOS image of Nisyros Island.

remaining 10 served as check points. For the second model, just four GCPs, not enclosing all remaining 34 points, were used. The four GCPs had height 2–3 m and one 34 m, thus, extrapolation errors both in planimetry and height could occur.

Starting from the regular DEM, the nodes were transformed by one of the two models into pixel space and were used as anchor points to bilinearly interpolate the pixel coordinates of the remaining orthophoto pixels (the orthophoto had a pixel spacing of 1 m). Then, the grey values were interpolated by a bilinear interpolation. The orthophoto was generated for each spectral channel separately with own software, using the same parameters, except the input image of course (see Fig. 5).

6. Orthophoto postprocessing and visualisation

The three channels were first filtered to reduce noise. Typical IKONOS noise is (a) chess pattern noise (common for satellite sensors, increased through sharpening included in MTFC) and (b) vertical stripes, usually dark but sometimes bright (again typical for linear CCD arrays). A 3×3 low-pass filter, empirically determined and asymmetric (stronger smoothing in horizontal direction to account for the vertical stripes, was used. The filter coefficients were:

0.0375	0.075	0.0375
0.125	0.45	0.125
0.0375	0.075	0.0375

Other symmetric Gaussian filters and a median filter were used, with visually worse results. The aim was to smooth noise but without smoothing the signal too much. Then, a contrast enhancement via Wallis filtering (Baltsavias, 1991) was applied with the same parameters for all three channels. This filter also causes a radiometric equalisation of the images.

The original and preprocessed orthophotos of each channel were combined in one RGB image in Photoshop. The postprocessed orthophotos show much more

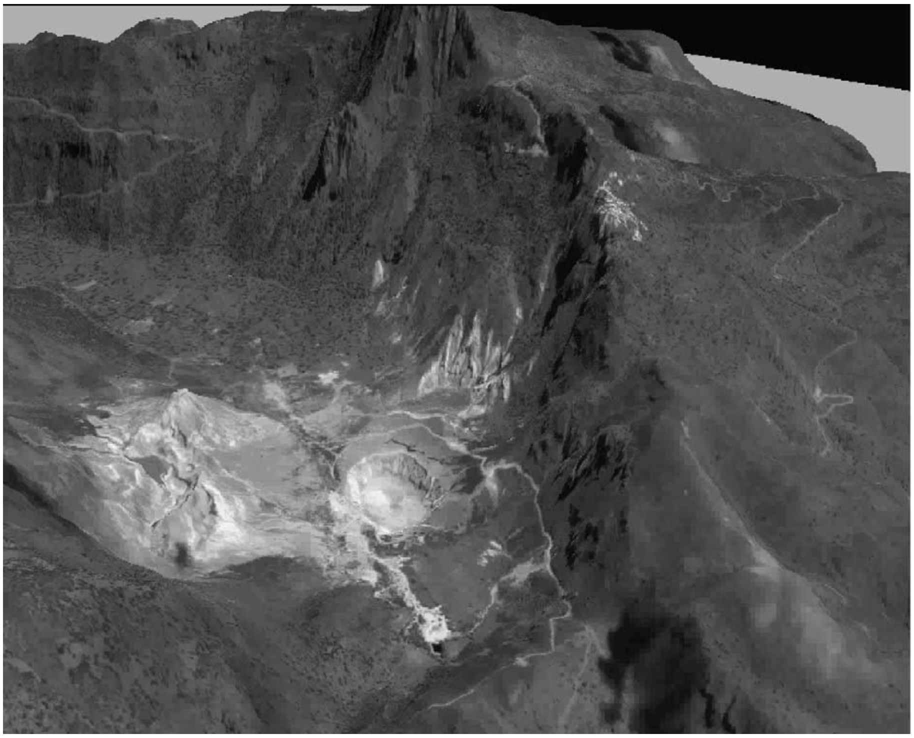

Fig. 6. A single image of a fly-through video generated using the orthophoto and the DEM with Erdas Virtual GIS.

details than the original. There is a slight saturation in 0 and 255 with trees/shadows and roofs/water, etc., respectively. The postprocessed RGB looks mostly like a B/W (due to the radiometric equalisation caused by Wallis filtering). There are some regions where R grey values are higher (e.g. vegetation) or lower leading to blueish/green areas, e.g. dirt roads, some man-made objects. Thus, for visualisation purposes, the postprocessed RGB orthophoto channels were manually changed in Photoshop.

After these investigations, a more thorough analysis of radiometric noise and artifacts of IKONOS images was performed and better radiometric improvement methods were developed (see Baltsavias et al., 2001). These methods can be applied directly to 11-bit image, include local adaptive nonlinear noise reduction, based on automated noise estimation for each image, more automated setting of the Wallis filter parameters and various optimised reductions from 11 to 8 bit. These preprocessing methods are usually applied to the original images, before orthophoto generation.

Using the orthophoto and DEM, 3D visualisations, fly-throughs and a video were generated using ERDAS Virtual GIS. Fig. 6 shows a snapshot of such a video, where fairly small scene details, like narrow paths, can be well recognised.

7. Geometric accuracy analysis of original IKONOS image and orthophotos

The planimetric accuracy of the delivered IKONOS images was assessed using the GCPs. The errors vary proportionally to the terrain height and are much larger than the error specified by Space Imaging for Geo, since the latter does not include errors due to relief and the inflated ellipsoid, as mentioned above (see version 1 in Table 2). The accuracy of the orthophotos using the two sensor models mentioned in Section 5 was also assessed with the GCPs. They were measured in the orthophotos by taking their known coordinates from one channel of the original image and transferring them semiautomatically in all orthophotos by least squares

Table 2
Accuracy analysis of original Geo images (version 1) and produced orthophotos (see explanation of versions in text)

Version	Image type / control points	Check points	Mean with sign (m)		RMS (m)		Maximum absolute (m)	
			X	*Y*	*X*	*Y*	*X*	*Y*
1	PAN-MSI	38	− 102.6	70.0	106.1	75.5	153.1	122.8
2	PAN-MSI/4	34	− 0.7	0.2	1.7	1.0	4.4	2.3
3	PAN-MSI/4	15	− 0.6	− 0.1	0.9	0.6	1.5	1.4
4	PAN-MSI/28	10	− 0.3	1.0	1.8	1.5	4.4	2.6
5	PAN-MSI/38	0	− 0.4	0.8	1.5	1.3	3.7	2.3

matching. These pixel coordinates were transformed to the EGSA system and their height interpolated in the DEM. The later shows just the DEM accuracy including effects from orthophoto errors (e.g. planimetric shifts cause height errors). The results of this accuracy analysis are listed in Table 2. Version 5 using Kratky's PMF with 38 GCPs is slightly more accurate than version 4, using the same model with 28 GCPs. This is natural since in the first case, no independent check points existed, and the polynomial terms were fitting

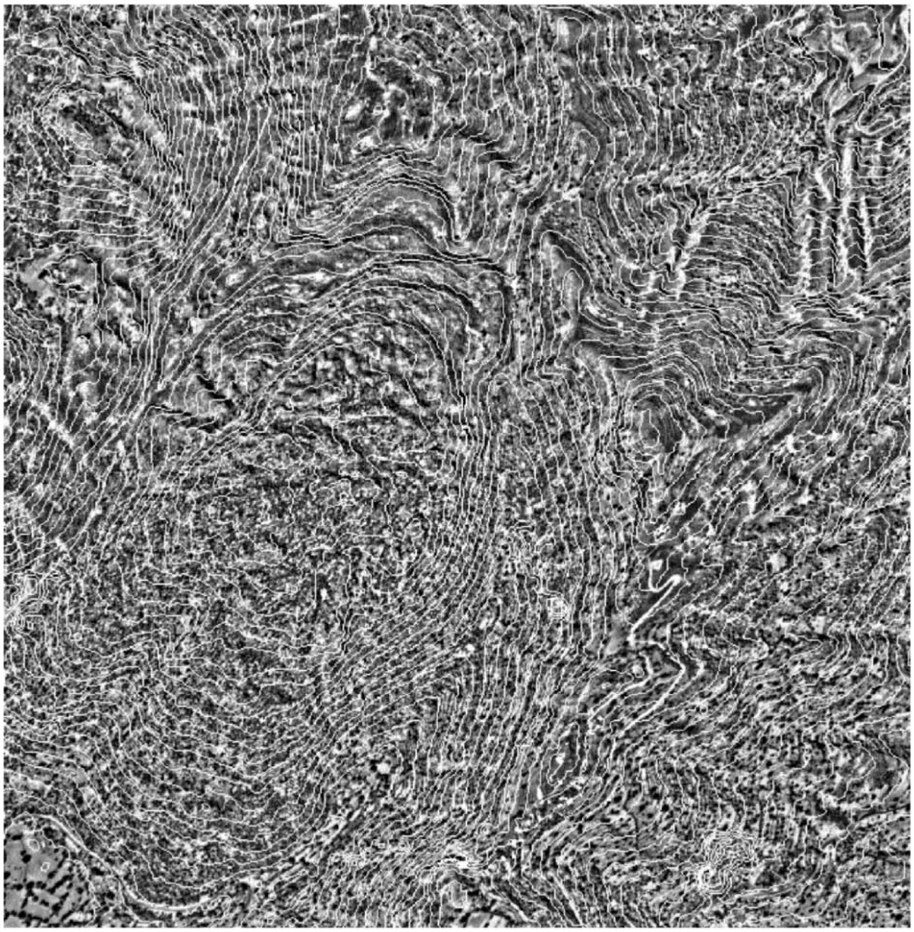

Fig. 7. An image region overlaid with contours, with 10-m interval generated from automatic image-matching results using two multitemporal IKONOS Geo images.

well to the GCPs. Version 2 using the affine transformation was not better than version 5 as was initially expected, probably due to the poor definition, and thus pixel-coordinate accuracy, of the GCPs. However, even if the accuracy was only similar, the number of needed GCPs, and the associated costs and efforts, were much less. Note also that although the check points had much different heights than the four used GCPs (see Section 5), no height extrapolation errors occurred. Version 3 is like version 2 but only with the points that were well identifiable and measurable, and shows the accuracy potential with good GCPs. The larger RMS and maximum absolute error in X for all versions is expected (terrain influence is in CCD-line direction, which is closer to X). The achieved accuracy is better than for the Precision product of Space Imaging, while the costs of the latter are ca. five times higher than Geo, and its radiometric quality worse than our postprocessed orthophoto.

In another IKONOS test (Fraser et al., 2002) where well-defined GCPs with 1–2-dm accuracy in both object and pixel space could be used, planimetric accuracy reached a level of ca. 0.3 pixel (0.3 m), showing the high geometric accuracy potential of IKONOS and, at least for such small scenes, a stable sensor geometry. Furthermore, at the same test it was shown that simple alternative sensor models, including the relief-corrected affine transformation, are more accurate than the RPCs, which can, since middle of 2001, be delivered by Space Imaging for Geo products, but at a significant surcharge.

Compared to other IKONOS orthorectification projects in Switzerland using panchromatic Geo images (see Baltsavias et al., 2001), with more, equally well-defined GCPs, similar or larger height range and sensor elevation, and partly more accurate but in all cases less dense DEM, a similar orthophoto accuracy has been achieved. However, in this study, we have an image

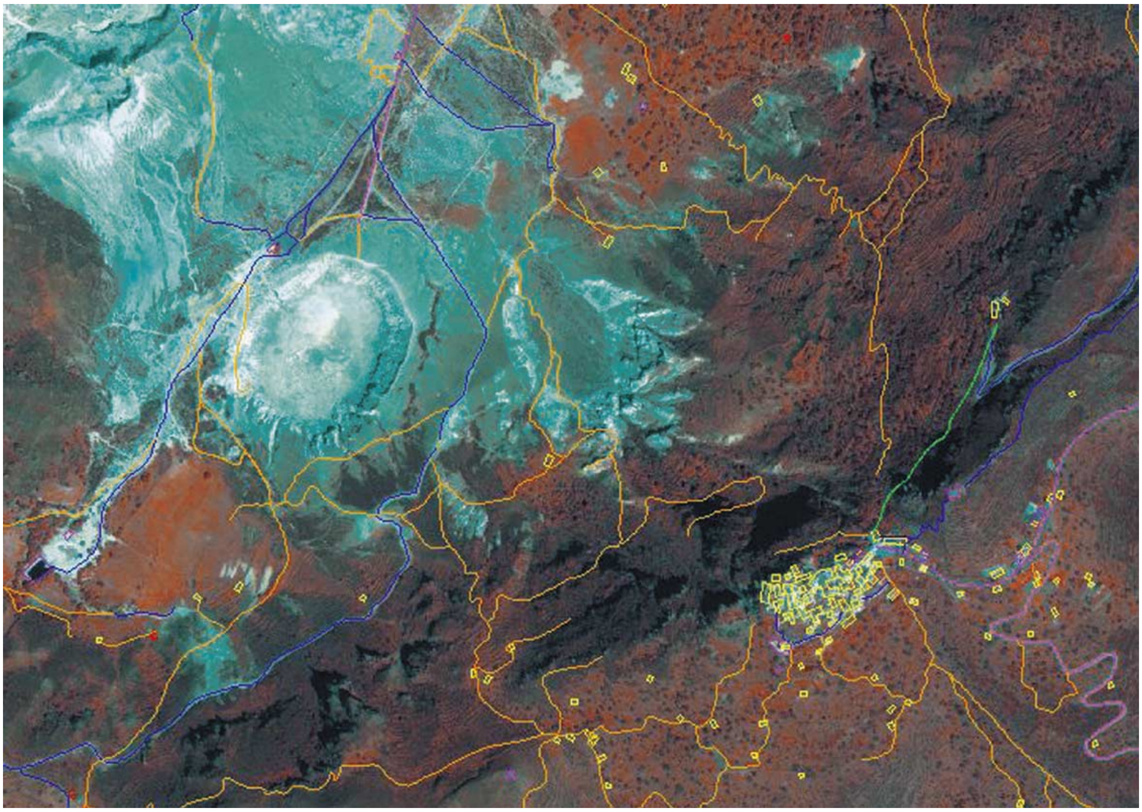

Fig. 8. The orthorectified IKONOS satellite image overlaid by the topographic information (roads, buildings, etc.) derived from field work and IKONOS. It represents a useful support for the topographic map update.

that comes from panchromatic and three 4-m resolution multispectral images. In addition, the unknown sharpening algorithm may cause certain geometric and radiometric errors. Thus, all in all, the results can be judged as better than the previous in Switzerland.

8. Further work

Using the two IKONOS images mentioned in Table 1, an attempt was made to generate a digital surface model (DSM) automatically using self-developed image-matching techniques from the two multitemporal Geo images. Although the sun illumination and land-cover conditions were fairly similar in both images, the position of clouds (and their shadows) differed, as well as the atmospheric conditions (image clarity) and the water surfaces due to varying wind speed. Using different matching techniques and matching parameter options, and without using any manual editing, but after manual exclusion of the cloud areas, the best version gave the following accuracy values using the DEM presented in this paper as reference (matching-reference): RMS, 3.2 m; mean with sign, 1.4 m; maximum absolute error, 97.4 m. These results are very encouraging and show the potential of DSM generation from IKONOS Geo, even with multitemporal images. The maximum accuracy potential should be even higher if one considers that the reference DEM was about as accurate as the one derived from IKONOS, that a significant bias (mean with sign), which could be potentially removed, existed, and that the RMS and mean with sign were influenced by large blunders, caused by faint remaining clouds which were not manually excluded, and thus led to much higher elevations in the matching results. More details on these investigations can be found in Zhang et al. (2002), while an example of the DSM generated by matching is shown in Fig. 7.

The final orthorectified IKONOS image is a useful tool for the high-accuracy orthophoto mapping. Thus, the update of the topographic map of Nisyros with a

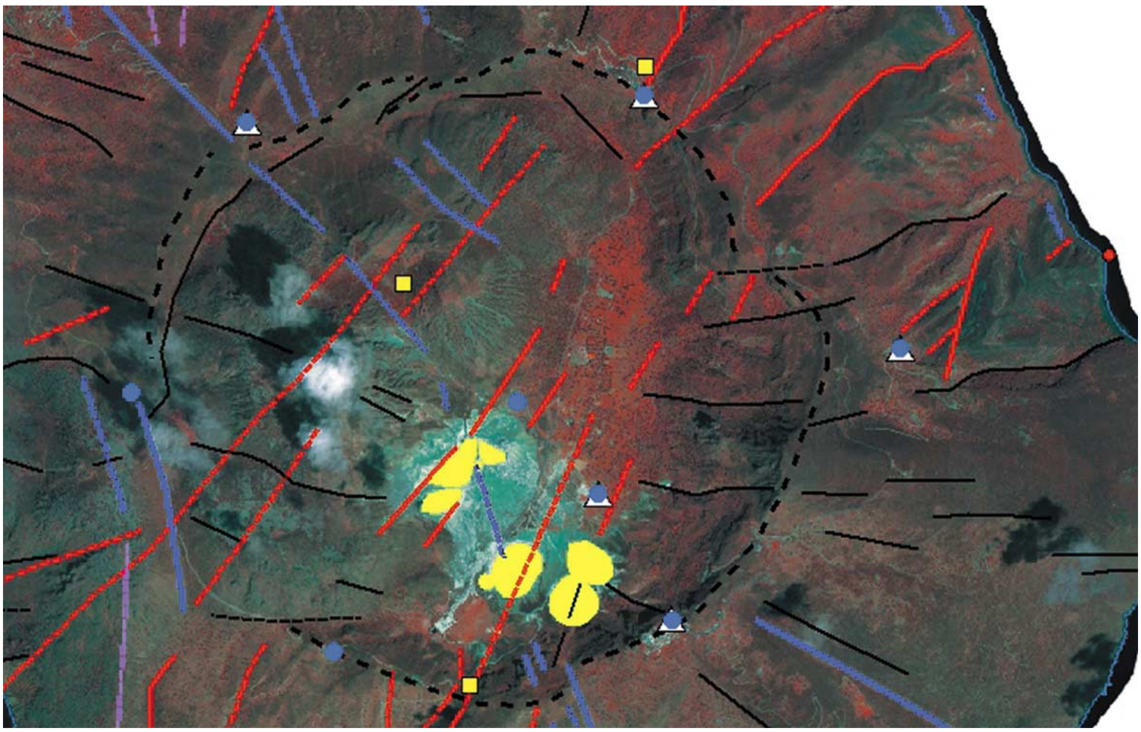

Fig. 9. The orthorectified IKONOS satellite image overlaid by the tectonic features (i.e. faults classified in categories, the position of GPS stations (blue circles), microgravimetric stations (triangles), fumaroles (squares)).

final scale of 1:10,000 (scale was changed compared to the original map 1:5000), including detailed information related to all topographic data layers has already started. After postprocessing, the orthophoto was used for updating the island's roads and paths. For the mapping of all categories of buildings (i.e. houses, churches, ruins) and land use classes (i.e., settlement areas, cultivated areas, forest, cliffs, barren land), the image is used without postprocessing. Although the terrain does not feature many visual obstacles preventing an undisturbed aerial view, it proved to be necessary to check the geo-objects to be updated in the field. We were using ink-jet printouts of the orthophoto with overlaid vector information from the topographic map for the fieldwork. The limited contrast of these prints were another drawback compared to the more brilliant representation on an RGB computer screen. The final updated topographic map will contain all topographic data, cartographically redesigned and classified in the mentioned categories. Additionally, it is planned to combine certain map layers with additional thematic information, such as geology, tectonics, seismicity, etc., and with the orthophotos in order to create image-based maps (Figs. 8 and 9) (Lagios et al., 2001; www.geowarn.org; www.space-unit.gr).

9. Summary and outlook

The IKONOS orthophoto can be further used for various visualisations. The base map can serve for representation of the positions of the DGPS, transfer of points from the IKONOS orthophoto to other imagery, geothermy, geochemistry and other measurements. It is also a useful tool regarding geology, tectonics, geomorphology, etc., not only in the laboratory (for the interpretation and digitization), but also during field work serving as a base map. Generally, the image will serve as a navigational tool for the Early Warning and Emergency Planning of Nisyros Volcano.

The ortho-images with high resolution and specifically the ortho-IKONOS images (1-m resolution) can provide useful information regarding the geology and the geodynamics of a region, as well as to contribute to various geo-environmental applications, both in the laboratory and in the field.

These corrected satellite images, apart for general visualizations, may be used in the following domains, and serve various purposes, such as:

(i) for the production of various ortho-maps relating to topography, land use, tectonics, neotectonics, morphotectonics, geology and geomorphology;
(ii) a base map for the location of the GPS measurements or stations in applied disciplines of geosciences (geophysics, seismology, geothermics, geochemistry, hydrogeology), both in the field and the laboratory.

Subsequently, these corrected images can be used as navigational tools for emergency planning, in crisis management and evaluation procedures in devastated areas due to any natural disaster (floods, forest fires, earthquake devastation, volcanic eruption), as well as a useful tool for all nonaccessible areas without proper maps. Within GEOWARN, both the classical map and the orthophoto will also be integrated in a web-based user-friendly interactive atlas information system allowing the combination with other thematic data and an extended analysis and visualisation functionality (Schneider, 2002).To conclude, it can be stated that the IKONOS 2 orthoimage of Nisyros Island and its derivates, will serve as a very important tool for the Early Warning and Emergency Planning of Nisyros Volcano.

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