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Best period for high spatial resolution satellite images for the detection of marks of buried structures

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Abstract Improvements in sensor technology in recent decades led to the creation of ground, air and space imaging systems, whose data can be used in archaeological studies. Greece is one of the lucky areas that are rich in archaeological heritage. The detection of prehistoric/historic undiscovered constructions on satellite images or aerial photos is a complex and complicated matter. These marks are not visible from the ground, they can, however, be traced on satellite or aerial images, because of the differences in tone and texture. These differences appear as crop, soil and shadow marks. Undoubtedly, the detection of buried structures requires a suitable spatial resolution image, taken under appropriate meteorological conditions and during the best period of the vegetation growing cycle. According to the pertinent literature, detecting covered memorials may be achieved either accidentally or, usually, after a systematic investigation based on historical narratives. The purpose of this study is to determine the factors that facilitate or hinder the detection of buried structures through high spatial resolution satellite imagery. In this study, pan sharpened images from the QuickBird-2 satellite were used, of a spatial resolution of 0.60-0.70 m. This study concerns the detection of marks of the ancient Via Egnatia, from the ancient Amphipolis to Philippi (Eastern Macedonia, Greece). We studied different types of vegetation in the region and their phenological cycle. Taking into account the vegetation phenological cycle of the study area as well as the meteorological data, four pan sharpened QuickBird-2 images of a spatial resolution of 0.60–0.70 m. were used, during four different seasons. By processing the four images, we can determine the one acquired during the most appropriate conditions for the detection of buried structures. The application of this methodology in the study area had positive results, and not only was the main

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purpose of this study – the detection of parts of the ancient Via Egnatia – achieved, but the locations of dozens of other buried archaeological remains were also determined.

1. Introduction

The panchromatic aerial photography is used in archaeological studies from the early 20th century. Improvements in sensor technology in recent decades led to the creation of ground, air, and space imaging systems, with adequate data to be used in studies of archaeological heritage. During the last decade, in Greece, an extensive research in the region of Eastern Macedonia (Figs. 1 and 2), from ancient Amphipolis to Philippi (in a place where human activity started from the Bronze Age and flourished during the Roman period), a total area of 500 km^2 (Fig. 2), was launched to detect marks of archaeological interest, with the traditional methodology of panchromatic aerial photographs and the use of modern technology, namely that of satellite images of high spatial resolution and digital detection techniques (Kaimaris, 2006). The result of this research was the detection of dozens of marks of buried structures and the introduction of this technology to the Greek archaeological community.

The Amphipolis was founded in 437 BC (Fig. 2). Archaeology has uncovered remains at the site dating to approximately 3000 BC. Due to the strategic location of the site it was fortified from very early. Xerxes I of Persia passed during his invasion of Greece of 480 BC. After the Athenians, in 357 BC Philippos II (father of Alexander the Great) removed the block which Amphipolis presented on the road to Macedonian control over Thrace by conquering the town. Amphipolis became one of the main stops on the Macedonian royal road and later on the Via Egnatia, the principal Roman Road which crossed the southern Balkans. By following the Via Egnatia, east was the ancient city of Philippi.

The history of the Philippi (Figs. 2 and 5) settlement started in the 360/359 B.C. (besides the Acropolis that is dated back to the Early Iron Age), when the colonists from Thasos founded

Figure 1 Map of Grecce.

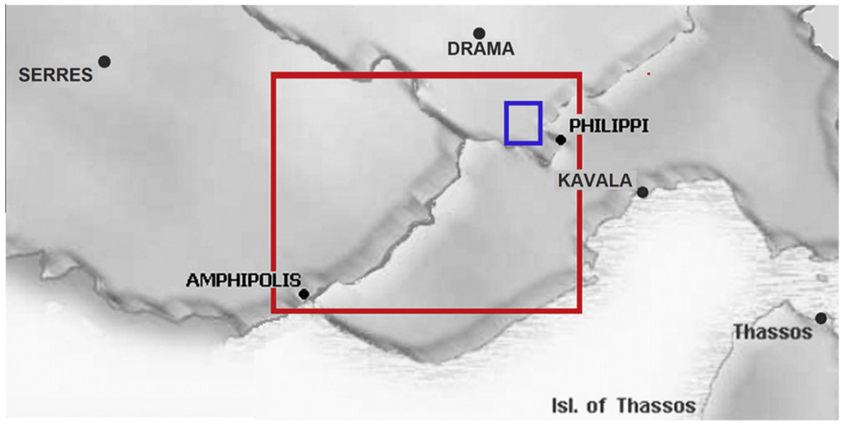

Figure 2 In the red frame is the wider study area (in the black frame in Fig. 1). In the blue frame the place of assessment of remote sensing data (Fig. 5).

there the first city (Krinides). When in 356 B.C., they were threatened by the Thracians, they asked for the help of Philippos II. He predicted its economic and strategic importance, occupied, fortified the city and he renamed it after himself to Philippi. In the plain of Philippi, in 42 BC there was the great battle between the Democratic and Aristocratic that imposed a new regime in the Roman Empire after the assassination of Julius Caesar. After the battle of Philippi (42 B.C.), the city becomes a roman colony and gained importance because of its position on the Via Egnatia.

The digital satellite image, which began in the early 70s with the launch of the first NASA commercial satellite Landsat-1, presented no interest – due to its low spatial resolution – for it to be used in archaeological studies. But in 1999 and 2001, with the launch of high spatial resolution satellites IKONOS-2 (the PAN having a spatial resolution of 1 m and the MS of 4 m) and Quick-Bird-2 (the PAN having a spatial resolution of 0.6 m and the MS of 2.5 m), a great interest for archaeological studies was created, especially in countries of rich archaeological heritage. Thus, in the last decade many techniques of detection and mapping of regions or residues of archaeological heritage have been developed (Beck, 2007; Campana, 2002; Larsen et al., 2008; Lasaponara and Masini, 2007; Lasaponara et al., 2008; Masini and Lasaponara, 2006a,b; Masini et al., 2008).

Buried structures often present/leave crop or soil marks on the ground, which, under appropriate conditions, can be detected from the space (with a bird's view). The ground in these places is often "degraded" (Beck, 2007; Lasaponara and Masini, 2007; Masini and Lasaponara, 2006a,b; Betti, 1963; Pierluigi, 1984; Brooks and Johannes, 1990; Winterbottom and Dawson, 2005). Areas with soil marks often constitute remains of a trench, of buried walls, etc. A pit or trench is filled with materials, which usually have different characteristics, different density and composition, and lead to disruption of the local soil profile.

The crop marks are an indirect effect of buried structures. Their visibility depends on the condition of soil, the climate and the vegetation. Positive crop marks appear in areas with subsurface trench. The cover material retains dampness, resulting in the plants growing more and maturing later than those in neighbouring sites. Negative crop marks appear in areas where the plants grow over the buried remains of human structures, where the soil is poor in nitrates, with no dampness and therefore it cannot help plant growth. Therefore, the phenological cycle of vegetation cover of the area with buried remains of the past is either positively or negatively affected, depending on the species present underground (Beck, 2007; Lasaponara and Masini, 2007; Masini and Lasaponara, 2006a,b). Soil marks are also created on the bare ground due to the difference in dampness and texture (Masini and Lasaponara, 2006b; Masini et al., 2008; Betti, 1963; Pierluigi, 1984; Featherstone et al., 1999; Barnes, 2003; Hanson and Olten, 2003; Wilson, 1982; Agache, 1963; Barrett, 1993; Bewley, 1996, 2003; Brown, 1998; Becker et al., 2004; Chevallier, 1963; Ciminale and Ricchetti, 1999; Cowley, 2002; Scollar, 1963; Jalmain, 1963; Martin, 1990; Nagy, 1991).

The crop and soil marks on the images appear as tonal differences, which, with the appropriate digital processing techniques, can be improved/ strengthened. In this study, we present the detection of marks of archaeological interest and of specific parts of the ancient Via Egnatia, from the ancient Amphipolis to Philippi (Eastern Macedonia, Greece). HRS images from the QuickBird-2 satellite were used, the PAN with a spatial resolution of 0.6 m and the MS of 2.5 m.

The purpose of this study is to find the best time for the acquisition of satellite images, which entails the combination of the study of the soil, the vegetation cover phenological cycle and the meteorological data, which facilitate the detection of the marks of the buried constructions.

2. Theoretical approach of the best period for mark detection

Utilizing the information of the types of soil cover and particular crop characteristics of the study area, i.e., wheat, cotton and corn (data source: National Statistical Service of Greece 1999), helped define the theoretically best period for mark detection in remote sensing images of different dates.

The *wheat* is planted in autumn at a depth of 2 cm, while its fertile depth does not exceed 3 cm. It is harvested in late June and it needs coarse soil for its development. At least the minimum rainfall should occur during the spring. Its height ranges from 0.7 to 1.2 m and its root system is superficial. The soil temperature should vary between 2 °C and 30 °C and the air temperature between 2 °C and 35 °C.

Therefore, in theory, the study area is covered in coarse material; the plant achieves an adequate height, a minimum depth of root system and the original cover material of the monument is preserved. The variations in air and soil temperature are conducive to both the sealing of dampness in the soil and its evaporation. From autumn to February, the plant grows very little, so traces of vegetation cannot be detected. From late May to late June (June harvest), the plant becomes "yellow" (mature), rendering observations of ground traces significantly difficult. Thus, the period of observation of traces relates to the period of wheat growth from late March to mid-May, i.e., a period of 45 days (Fig. 3).

The soil marks can be seen from late June, after the harvest, to February, after the plan has achieved/had a slight development. This period is long, but it is expected that the observations will be frequent in summer, after a temporary rain, or in autumn, after the first rainfall.

The root system of *cotton* ranges from 15 to 50 cm and its height from 0.6 to 1.2 m. It is therefore possible to observe strong differences in plant height, if the depth of the site is of less than 50 cm. This plant thrives in temperatures of 20–38 °C, in ground temperatures from 12 to 35 °C, and requires warm, dry climate with little rainfall. The seeding depth is 1–2 cm, while the fertile depth is less than 15 cm. Thus, the initial cover material is largely preserved. Finally, the planting is performed in spring and the harvest in autumn.

From April (planting) until late May, observations of the traces of vegetation cannot be performed due to the limited/scarce/slight plant growth; nor from early September until harvest (late September, early October), due to the white colour of the fruit and the final development phase. Therefore, the best period starts in late May and continues until late August (more than 3 months). Because of the great depth of the root system, observations can be improved.

From mid-October (harvest) to late May (limited/scarce/slightplant growth), soil marks will appear, perhaps after the first rains of autumn, or with the spring rise in temperature.

Corn has the same growing season as cotton and it grows in similar soil and climate conditions. Therefore, the observation periods of marks are similar to those of cotton, but of a different frequency. Its surface root system will most likely lead to the observation of weaker traces of vegetation.

The aforementioned theoretical conclusions, regarding the best period for mark detection, are presented in Fig. 3.

In analysing Fig. 3, we conclude that, in theory, the best period for mark detection spreads from *mid April* to *mid May* (one month, *First Period*) and form *late June* to *late August* (two months, *Second Period*). During the first period, marks of wheat growth will be observed as well as soil marks where cotton and corn have been cultivated, while in the second period traces of vegetation will be observed where cotton and corn have been cultivated as well as soil marks where wheat had grown.

3. Consolidating of the theoretically best period for mark detection

After a systematic search in the aerial photographs archives of various authorities (Hellenic Military Geographic Service-HMGS, Hellenic Mapping and Cadastral Organization-HMCO and the Ministry of Rural Development) 320 vertical, black and white aerial photographs, dating from 1945 to 1996,

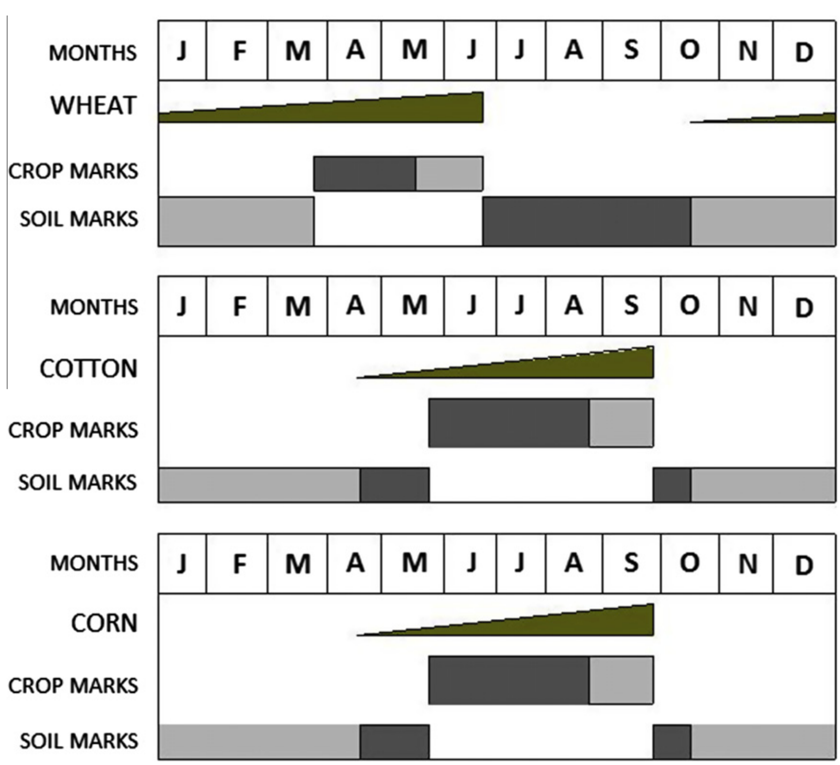

Figure 3 Theoretically, the period for mark detection. In green colour: the growth of crops. In light grey colour: the observation period and in dark grey colour: the best period for mark detection.

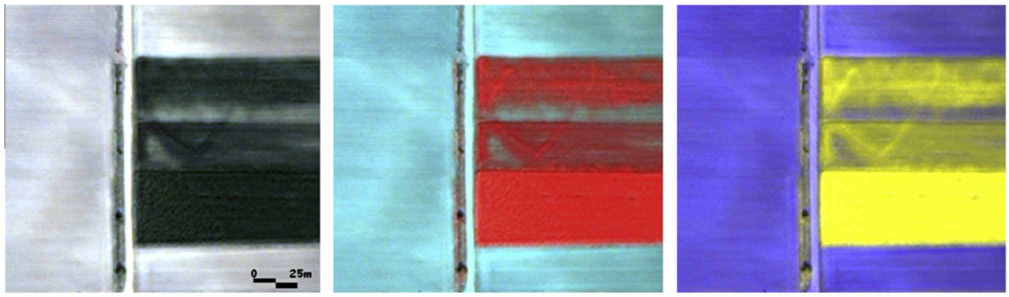

Figure 4 Covered perimeter trench. The first image is a fragment from the QuickBird-2, 02-05-2005, Data fusion, Channels: 1, 2, 3 = natural colours. In the second image, the third channel (Red) is replaced by the fourth (infrared). In the third image, the first three channels of the PCA are used.

of a scale of 1:42,000 to 1:6,000 were discovered. Unfortunately, meteorological data for these dates are not available in the archives of the National Meteorological Service (NMS). Thus, the observation of a buried construction mark that is common on the images of the overlapping diachronic aerial photographs could not lead to reliable conclusions about marks' detection. This situation occurs because various factors (e.g. unknown extreme meteorological phenomena, vegetation, etc.) that allowed the appearance of the mark may not appear in previous or subsequent shots. Besides, how can the analogical remote sensing data spreading over 10 or 20 years (e.g. 1945, 1953, 1965, 1985, 1996) be evaluated, since the materials (films, filters) and the shooting systems were constantly improving and the successive changes in the distribution of land caused changes in the landscape and covered the buried structures?

Taking into account the whole number of the optical satellite system receivers, it was decided (research begun in 2002/2003) that the satellite QuickBird-2 should be studied, because, on the one hand, it is not frequently used in Space Archaeology and, on the other hand, it has the ability to detect alterations in the size of the ancient Via Egnatia in size and vegetation. The composition (data fusion) of panchromatic and multispectral images allowed for the observation of natural colours in the smallest possible spatial resolution offered by the satellite system. In particular, the use of the fourth channel (infrared band) also helped the visual interpretation. The compression of the new synthetic images was proven most valuable, using the transformation of the principal PCA components (the combination of the first three new channels was rated as the most suitable for visual interpretation, since it allowed for optimum marks observation, Fig. 4).

Table 1 The time of satellite data reception for the assessment of the ability to detect marks.

Image dating		Theoretically first period for best mark detection
24/11/2003		Out
29/04/2004	10/05/2003	Inside
10/06/2003		Out

In this study, we will try to consolidate the *Theoretically First Best Period for Mark Detection* (mid April to mid May) through the comparison of the common marks frequency on

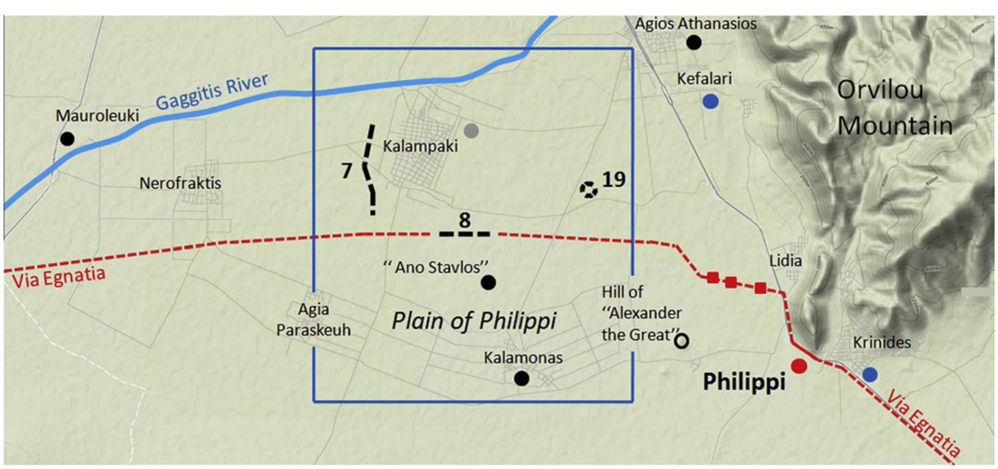

Figure 5 In the blue frame the place of assessment of remote sensing data. In blue circles the settlements of the Late Neolithic Period till the Roman Period. In grey circle the settlement of the Neolithic Period till the Roman Period. In red circle the settlement of the Early Iron Age till the Roman Period. In black circle the settlements of Historical till the Roman period. With dotted red line the path of Via Egnatia according to the marks and with red squares the locations of the excavational trenches of Via Egnatia. With dotted black line the locations of marks nos. 7, 8 and 19 (3 of 29 marks) of Table 2.

the diachronic overlapping satellite images (remote sensing assessment data) (Table 1) in an area of 30 km^2 (Figs. 2 and 5). At the same time, the great ability of the satellite QuickBird-2 to detect marks was also tested. Unfortunately, dated data within the *Theoretically Second Best Period for Mark Detection* was not available for the study area.

In order to collect a sufficient number of common marks, so that the result of the assessment is reliable, they were used not only the marks of possible detected parts of Via Egnatia, but also a significant number of unknown buried or modern constructions and covered streams. The restrictions agreed in order to avoid the wrong choice of marks caused by a random event were:

- if the mark is observed only on one satellite image, while it spatially belongs to more than one, it has to be detected on aerial photographs,
- if the mark has not been detected on aerial photographs, it has to be observed on at least two diachronic satellite images,

Table 2 The intensities of observation of the common mark.

Image dating	Mark no. 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
	Intensity level																												
10/05/2003				1		2	3	4	2	1	2	4	1	1	1	3	3	1	3	4	3	3	4	3	3	3	3	3	3
10/06/2003	0				1	1	2		1	1		1	0	1					1	2	1	2			0				
24/11/2003		2	0	1	2	2	0	2	1	1	1	2	1	0	0				2	0	2	2			2	2	2	0	
29/04/2004	3	3	1	3	3	3	2	4		3	2		4	0	3	2	2	2		4		4	3	4	2	2	4	3	2

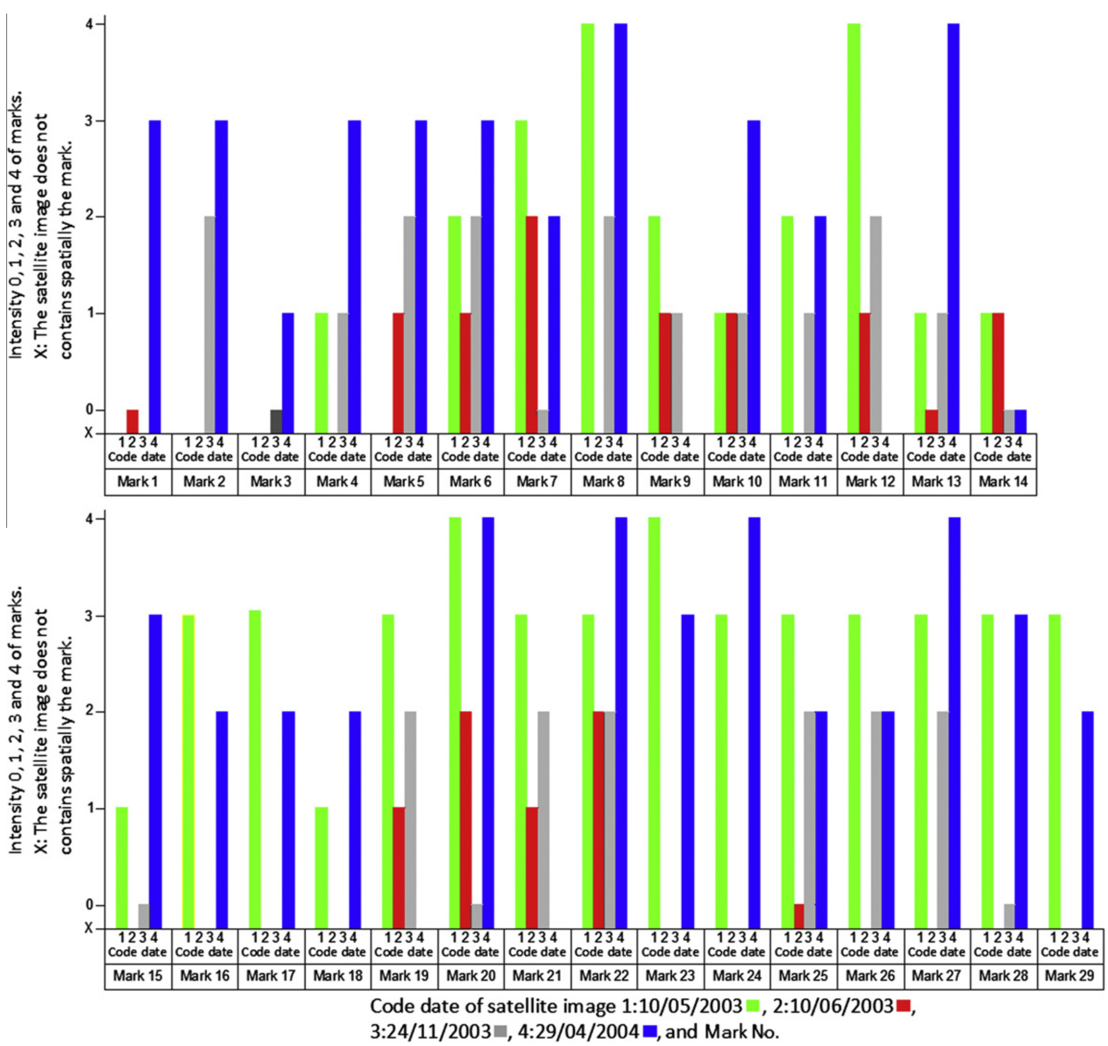

Figure 6 Diagram of the intensities of observation of the common mark.

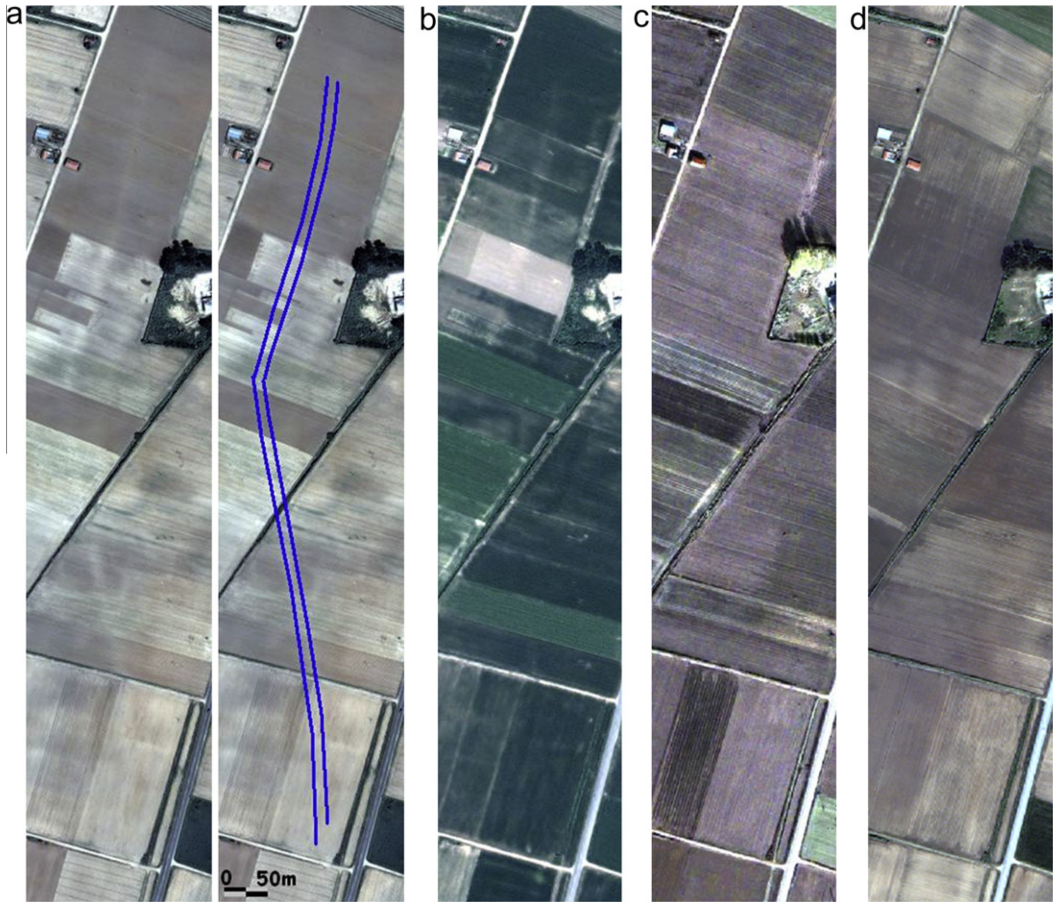

Figure 7 Mark no. 7, QuickBird-2, datafusion, channels: 1, 2, 3 = natural colours. (a) 10/05/2003, line mark buried constructions width ~10 m, Intensity: 3, (b) 10/06/2003, Intensity: 2, (c) 24/11/2003, Intensity: 0 and (d) 29/04/2004, Intensity: 2.

- the mark that does not fulfil the above restrictions must be proved to be related to a known buried construction (e.g. an old rural road).

The observation intensity of the common mark was assessed (optical assessment only) for each satellite image (e.g. Figs. 7–9) to which it belongs, ranging from zero, small, medium or satisfactory to great intensity, corresponding to values 0 or 1 or 2 or 3 or 4 (Table 2 and Fig. 6).

The study of Table 2 and Fig. 6 (comparisons of totals on the common marks between satellite data) concluded that the image dating on the 29/04/2004 shows a greater ability to detect marks and outruns all others. Next, in descending order, are the images dated 10/05/2003, 24/11/2003 and 10/06/2003. Specifically, the first image offers 19% better results than the second, 60% than the third and 64% than the fourth. The second image is 51% better than the third and 57% than the fourth. Finally, the third image gives 18% better results than the fourth.

The knowledge of the meteorological conditions, not only on the day of the image, but for a period of at least 30 days before it, might explain the frequency of observation of marks, propose general acquiring conditions and might ultimately justify or challenge the assessment result, if extreme meteorological phenomena have occurred (justification or rejection of the First Period). For this reason, the National Meteorological Service has measured the daily minimum, average and maximum temperature, the average dampness and rainwater height over a period of one month, until the day of every satellite image (Table 1 and Fig. 10).

On April 2004, daily temperatures and rates of relative humidity averaged out near normal for the season (Fig. 10.a). What is more, there were almost daily rainfalls of low intensity and duration, with a maximum of 21.4 mm (1 mm corresponding to 1 m^2 covered by 1 litter of water) nine days before the images were taken. Therefore, there should have been no strong marks, due to the continuing – even of low intensity – rainfalls, the humidity which was above normal for the season (preventing evaporation) and the rise in temperature (transition from winter to spring). However, this particular growing season and the quality of the soil have given strong marks and were considered ideal for their appearance, because of the significant role that the image dated 29/04/2004 has taken after the assessment (average temperature 15.7 °C, relative humidity 64%, absence of rainfall on the day of the shot). Possibly slightly higher temperatures (not extreme) or less rainfall would further improve the frequency and increase the number of marks.

In the first ten days of May 2003, high temperatures for the season (Fig. 10b), lower rates of relative humidity and little rain was observed. Therefore, the satellite image dated 10/05/2003 second place – by a thread – (average temperature

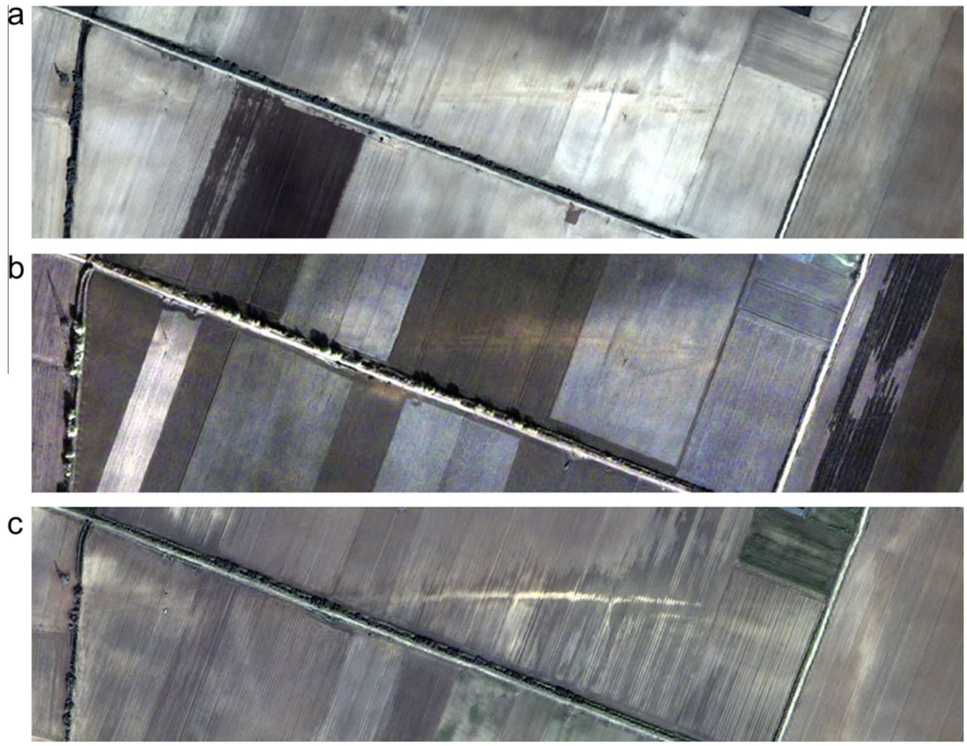

Figure 8 Mark no. 8, QuickBird-2, datafusion, channels: 1, 2, 3 = natural colours. (a) 10/05/2003, line mark buried constructions (Via Egnatia) width ~7 m, Intensity: 4,(b) 24/11/2003, Intensity: 2 and (c) 29/04/2004, Intensity: 4.

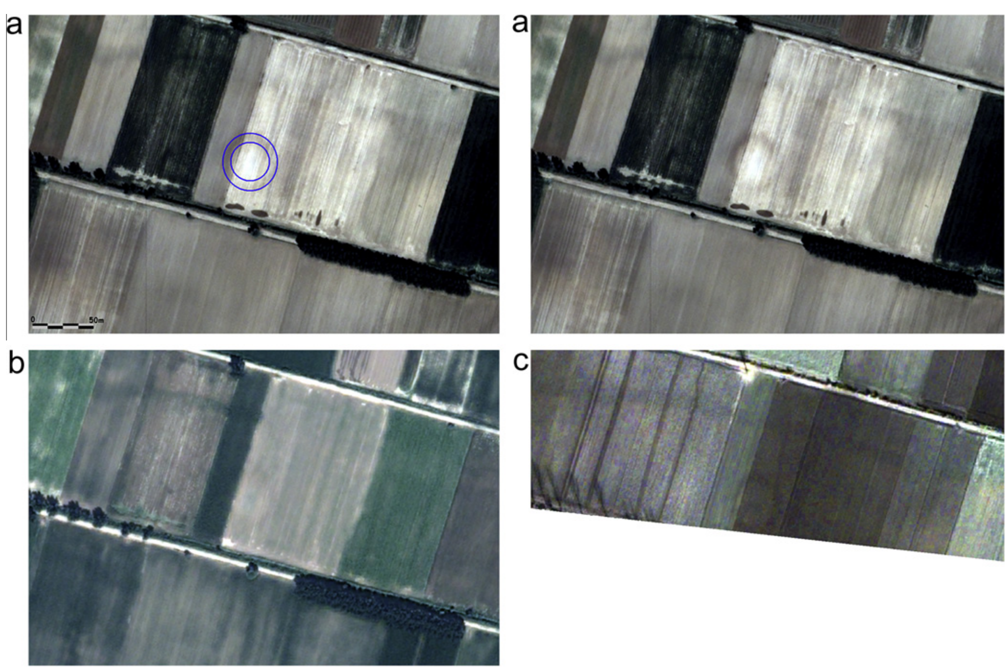

Figure 9 Mark no. 19, QuickBird-2, datafusion, channels: 1, 2, 3 = natural colours. (a) 10/05/2003, circular mark with exterior diameter 45 m and width of ring 5.5 m, Intensity: 3. (b) 10/06/2003, Intensity: 1 and (c) 24/11/2003, Intensity: 2.

25 °C, relative humidity 41%, lack of rainfall during the day of the image) is due to the relatively ''droughty'' study area (high temperature, low relative humidity, no rainfall), that resulted in the gradual colour balance of the marks and the environment. However, this particular growing season and soil quality enabled the appearance of adequate frequency and number of marks. It is possible that, in case of lower temperatures (within the normal specific period rates) or heavy rainfall two days be-

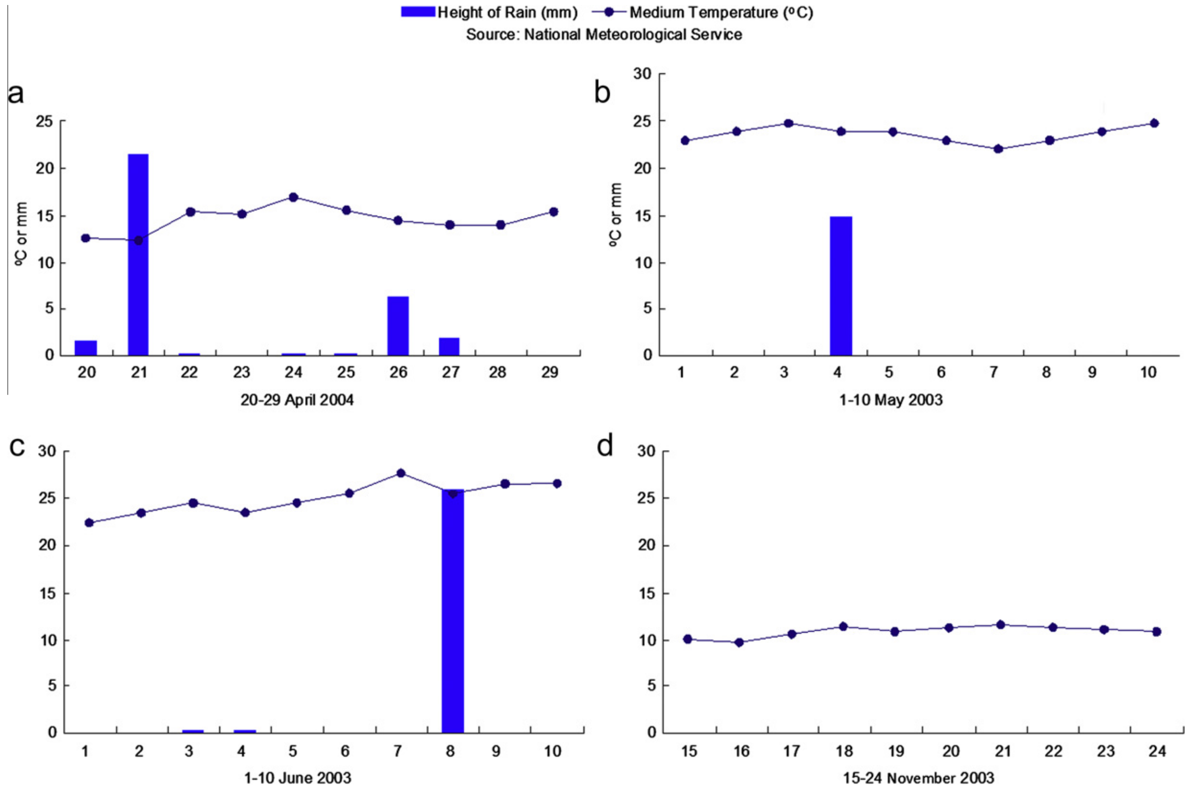

Figure 10 Illustrating the rainfall rate and the average temperature ten days before the images was taken.

fore the images, the frequency and the number of marks would be improved.

In the first ten days of June 2003, normal temperatures for the season (Fig. 10c) and rates of relative humidity were observed. While there were no rainfalls because of the specific season, a summer storm occurred two days before the images were taken (25.4 mm). One would expect this rainfall to be ideal for the appearance of marks, but, seeing the last position occupied by the image dated 10/06/2003 (average temperature 26.3 °C, relative humidity 53%, lack of rainfall on the day of acquisition), it is evident that despite normal conditions and the perfect coincidence of the rainfall, the plants growing season and the quality of the soil have prevented the appearance of marks. Suggestions for improving the observation would be utopian. Thus, observations in conjunction with conditions in June have boosted the *First Period for Best Marks Detection*, where the images of April and May belong.

In November 2003 there were higher temperatures for the season and normal rates of relative humidity (Fig. 10d). The extreme phenomenon of an almost total lack of rainfall combined with higher temperatures for the season allowed for the appearance of marks whose frequency and number is 18% higher than those in June and 57% lower than those in May 2003. Suggestions to improve the observations would also be utopian. In closing, November has consolidated, once again, the *First Period for Best Mark Detection*.

To sum up, this process has enforced the *Theoretically First Period for Best Mark Detection*. Thus it was speculated that a future image taken within that period, under normal meteorological conditions for the season, would allow for the observation of marks of adequate number and frequency.

4. Conclusions

The methodological procedure has proved invaluable, since with the *support* (assessment process of remote sensing data) of the *Theoretically First Period for Best Mark Detection* a new take was performed in the middle of this period with the QuickBird-2 that actually led to the detection of hundreds of new buried constructions. Certainly, the climatic conditions were fully known for a long time before and up to the time the image was taken, and they ranged within normal levels for the season. However, it is noted that the *Documentation of the Enhanced Period* requires programming the taking of images for some time, both within and outside the Period, with a full knowledge of the climatic conditions.

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