Archaeology through the keyhole: the serendipity effect of aerial reconnaissance revisited

Article *in* Interdisciplinary Science Reviews · January 2004

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Recently declassified US intelligence satellite photographs dating from the Cold War have been found to be a valuable source of historical overhead imagery for use in archaeological and other studies. Such civilian uses of material that was originally acquired for intelligence purposes represent salient examples of the 'serendipity effect' of aerial reconnaissance, whereby photographs taken for one purpose find, years later, a new value or use. This review describes the nature of declassified intelligence satellite photographs and the uses to which they have been put in archaeological and other scientific studies, and demonstrates the great scientific potential of this archive of historical material that has lain dormant for over thirty years.

Writing in these pages in 1989, Dino Brugioni described the concept of the 'serendipity effect' of aerial reconnaissance.[1] First coined by Arthur C. Lundahl, a former Director of the US National Photographic Interpretation Center, this phrase refers to the discovery in aerial photoreconnaissance imagery of 'bonus' material, unrelated to the primary intelligence aim of the mission, but which nonetheless represents a valuable discovery in its own right. Using images derived from both conventional aerial photography and civilian satellites, Brugioni gave illustrations of the 'serendipity effect' from fields as diverse as archaeology, meteorology, disaster prediction and prevention, and water resource management. However, because of security restrictions in place at the time he was writing, he was unable to refer to one of the most significant sources of US overhead strategic intelligence – the Keyhole (KH) series of photoreconnaissance satellites[2] – and their potential for serendipitous use. A decade later, the declassification of an extensive archive of photographs acquired by US intelligence satellites in the 1960s and 70s now allows this material to be used for civilian purposes. Thus, some thirty years after the images were originally acquired for intelligence purposes, formerly highly classified satellite photographs are now proving to be a valuable source of historical imagery for serendipitous use by aerial archaeologists as well as workers in other scientific disciplines.

AERIAL ARCHAEOLOGY

In order to appreciate the contribution that declassified intelligence satellite photographs can make to archaeological studies, it is first necessary to understand the role of aerial photography and the application of satellite remote sensing in archaeological prospection. Ever since the pioneering work in the 1930s of O. G. S. Crawford, the father of aerial archaeology, archaeologists have used aerial photographs acquired by aircraft flying at low and medium altitude to search for traces of the remains of past features and landscapes.

 DOI 10.1179/030801804225012635

Indeed, the technique has proved to be so fruitful that aerial photography is now considered to be a key method by field archaeologists when conducting archaeological investigations and landscape studies.[3]

Archaeological features apparent on aerial photographs are often described according to how they are revealed, and can range in size from earthworks several kilometres long to soil marks and crop marks less than a metre wide.[4] Earthworks are features that can be seen in relief. They are usually apparent on aerial photographs as highlights and shadows, but may also be seen as differences in vegetation cover, as well as through differential melting or drifting of snow cover. Their appearance is highly dependent on weather and lighting conditions, and they tend to be seen best when the sun is low in the sky, when shadows can accentuate relatively minor changes in height of features.

Soil marks reveal the presence of buried features such as ditches and foundations through changes in soil colour, as a result of parts of the features being brought to the surface by ploughing. Such features, which are destroyed gradually by the very act of ploughing that makes them visible, are most apparent in aerial photographs taken during the winter when fields are free of crops. Buried features can also be detected as crop marks, where the presence of the buried material can result in differential crop growth as a result of differences in moisture and nutrient availability. The marks can be seen in such crops as wheat, barley and some root vegetables and are critically dependent on soil type and conditions, weather during the growing season, agricultural practices and viewing angle relative to the sun. Indeed buried features that appear as crop marks can often be very elusive, being visible one year yet invisible the next.

In addition to amassing information that would be difficult to obtain otherwise through ground based prospection, the aerial perspective permits archaeological features to be seen within their landscape. This can provide a valuable perspective in understanding the roles and relationships of sites to each other and to the physical landscape in which they are located.[5]

Whilst light aircraft generally represent a good platform for acquiring aerial photographs, their utility can be constrained by a number of factors. Airspace restrictions, the bureaucratic challenge of obtaining permission to take aerial photographs in certain countries and the problems of operating in potentially hostile environments can hinder the use of conventional aerial photography for archaeological prospection. On top of this, the burden of acquiring and analysing a substantial number of photographs, each covering a relatively small area, in order to systematically cover a large survey area has the potential to create a logistics nightmare.[6] Remote sensing satellites with their 'open skies' nature and ability to collect relatively high resolution synoptic images covering areas of hundreds of square kilometres can overcome many of these drawbacks and have the potential to contribute significantly to archaeological research.

SATELLITE ARCHAEOLOGY

Early attempts to use satellite images in archaeological studies were hampered by their low spatial resolution and by the need for dedicated image processing equipment for their interpretation and use.[7] The eighty metre resolution of the multispectral scanner of the Earth Resources Technology Satellite, the first in what is now known as the Landsat series that was launched in 1972, precluded the detection of all but the largest of archaeological features, such as the pyramids at Giza,[8] ancient canals in Mesopotamia[9] and ancient rainwater concentrating structures in northern Egypt.[10] However some success was achieved with multispectral scanner imagery, as well as with multispectral images from the higher (thirty metre) resolution Thematic Mapper sensor carried on later versions of Landsat, through the use of image processing techniques and modelling to predict areas of high archaeological potential.[11] With the advent of ten metre resolution imagery from the French Spot satellite in 1986, smaller archaeological features came into focus, although the archaeological utility of the product remained constrained by its low spatial resolution.

Following the end of the Cold War, high resolution satellite imagery from the Russian space programme became available commercially in the 1990s. Of the various products that were marketed, KVR-1000 photographic imagery with a spatial resolution of approximately two metres was found to have the greatest potential for use in archaeology. A study of KVR-1000 imagery covering the environs of Stonehenge showed that it was broadly comparable with conventional medium scale vertical aerial photography and capable of detecting both upstanding archaeological features as highlights and shadows and plough levelled features as crop and soil marks.[12] Similarly, KVR-1000 imagery of the site of the former Greek and Roman city of Zeugma on the Euphrates in Turkey (see below) was found to be of great help in understanding the area and its sites.[13] For a period of eighteen months in the late 1990s, KVR-1000 imagery covering a significant proportion of the earth's surface was available for purchase over the internet from the terraserver[14] at relatively low cost. However, with the conclusion of this experimental venture in 2000, this particular source of low cost satellite imagery for archaeological research appears to be temporarily lost while the site transitions to a fully commercial venture.

Most recently, high resolution commercial imagery has become available from the Ikonos and QuickBird satellites. With spatial resolutions of 1.0 and 0.6 metres respectively for black and white panchromatic imagery sensitive to all visible wavelengths and the near infrared, and 4.0 and 2.4 metres for multispectral colour imagery covering each of the blue, green, red and near infrared bands, the products from these satellites have undoubted archaeological potential.[15] However, the very high cost of these images, together with the relatively limited cover that is currently available, currently limits their practical use by aerial archaeologists.

Archaeological applications of satellite imagery are not limited to the use of passive sensors such as those described above that detect solar radiation reflected from the earth's surface. By providing their own source of illumination, active radar sensors can sense a target area at any time of day or night and can 'see' through cloudy or dusty conditions that would otherwise obscure visible and infrared passive sensors. As noted by Brugioni in his original article on the 'serendipity effect', the flight of the Shuttle Imaging Radar-A (SIR-A) on the space shuttle Columbia in 1981 vividly demonstrated the ability of the radar to detect subsurface features in hyperarid regions. On radar images of the south-eastern Sahara desert in Egypt, ancient river systems now covered by up to two metres of dry sand were apparent, but were absent on Landsat images.[16] Excavations to verify these 'radar rivers' uncovered numerous Stone Age artefacts apparently associated with the palaeodrainage systems. The subsequent flight of the second generation SIR-B sensor in 1984 over the Sahara provided further data to support the initial findings from SIR-A,[17] and despite it being impossible to detect any archaeological features directly, these discoveries have contributed to the understanding of the palaeodrainage of the eastern Sahara and the Stone Age archaeology of the region.[18] Similarly, SIR-A imagery covering China's Taklamakan desert was able to detect 'radar rivers' some tens of metres under hyperarid sands.[19]

In less arid regions, portions of the Great Wall of China have been detected on imagery from the SIR-C radar flown in 1994,[20] as have details of the huge ceremonial complex at Angkor in Cambodia despite the area being shrouded under a dense rainforest canopy.[21] In West Africa, SIR-C imagery has also been shown to have some potential in detecting upstanding rectilinear walls associated with presentday and deserted settlements[22] and, recently, imagery from the ERS-2 satellite has been used to monitor erosion of the Nasca pampa in Peru to help preserve the spectacular geoglyphs of the 'Nasca lines' that are estimated to have their origins around 400BCE.[23] However, the relatively low resolution of current radar products (ten to thirty metres) together with the difficulties inherent in interpreting the products presently constrain the use of radar satellite imagery for archaeological studies.

DECLASSIFIED INTELLIGENCE SATELLITE PHOTOGRAPHS

On 22 February 1995, Presidential Executive Order 12951 directed the declassification of intelligence imagery acquired by the first generation of US photoreconnaissance satellites.[24] Some 866 041 photographic images that had been collected between 1960 and 1972 were subsequently transferred to the National Archives and Records Administration (NARA) and the US Geological Survey (USGS) Earth Resources Observation Systems Data Center, from whom copies can be purchased at very low cost.[25]

Over ninety-five per cent of the declassified photographs were acquired by satellites from the Corona programme, the first three versions of which were designated KH-1 through KH-3.[26] With an initial spatial resolution of the order of twelve metres, in the space of two years the spatial resolution of the panoramic cameras carried by these satellites improved to about four metres for the KH-3C‴ (C Triple Prime) camera. The next version of the satellite, the KH-4, brought the added advantage of stereoscopic photography taken by the M (Mural) camera and was subsequently followed by the workhorses of the Corona programme, the KH-4A in 1963 and the KH-4B in 1967. These systems had dual recovery systems that eventually extended mission life to up to eighteen days, and carried J-1 and J-3 cameras producing photographs with nominal spatial resolutions of 2.7 and 1.8 metres respectively (Fig. 1). Each frame from the J-3 cameras had a nominal ground coverage of some 16 by 217 kilometres, and on a typical mission each pair of cameras returned up to twelve thousand photographic frames.

Whilst the emphasis of the early missions was on acquiring coverage of intelligence targets in the denied territories of the former Soviet Union and China, coverage was extended to other parts of the world in later missions for mapping, charting and geodesy purposes. Early Corona missions averaged fifty to sixty per cent cloud cover, but over the lifetime of the programme this improved to approximately thirty per cent for the KH-4B missions of the late 1960s and early 70s as a result of improvements in satellite control and weather forecasting over target areas.[27] In total, it can be estimated that around eight hundred million square kilometres of cloud free photography of the earth's surface was collected by Corona, although many places were targets of repeat coverage over the programme's lifetime.

In addition to the 826 553 photographs acquired by Corona, getting on for forty thousand photographs from two further programmes, KH-5 Argon and KH-6 Lanyard, were declassified in 1995. Argon was a framing camera designed to provide mapping and geodetic data on the Soviet bloc in support of US military requirements.[28] A total of six successful missions took place between 1961 and 1964, returning some 38 578

1 Extract from Corona KH-4B satellite photograph covering the airfield at Farnborough, UK. The photograph was acquired on 17 August 1968 by mission 1104-2 and shows considerable fine detail including the high contrast runway markings and larger features such as taxiways, hardstandings and buildings. The spatial resolution of this photograph is estimated to be of the order of two to three metres for high contrast features (data available from US Geological Survey, EROS Data Center, Sioux Falls, SD, USA)

photographic frames. Whilst the frame area covered was high (approximately five hundred and fifty by five hundred and fifty kilometres), the spatial resolution was very low, at around a hundred and forty metres.

Lanyard was a panoramic spotting camera based on leftover hardware from the previously cancelled Samos programme.[29] Intended for interim use until a new US Air Force camera system – the KH-7 Gambit system described below – was fully developed and operational, only one of the three KH-6 satellites that were launched in 1963 successfully returned film. A total of 908 frames were acquired, comprising some thirty-five bursts of photographs, each burst covering up to approximately fourteen thousand square kilometres on the ground over the Soviet bloc and China, before the camera failed after thirty-two hours in orbit. Although the system demonstrated in a few instances that it had the potential to achieve the design goal of a ground resolution of 1.5 metres, significantly better than that being achieved at the time by Corona, the majority of the photographs were seriously degraded and of poorer resolution. Because of the success of the KH-7 system, the Lanyard programme was terminated after this one and only successful mission.

In October 2000, a further forty-eight thousand intelligence satellite photographs that had been acquired by the KH-7 Gambit surveillance and the KH-9 Hexagon mapping systems were approved for declassification and copies transferred to NARA and the USGS.[30] The KH-7 Gambit was the US intelligence community's first high resolution imaging satellite, which complemented the area search coverage of Corona with photography that had initially a best spatial resolution of 1.2 metres, subsequently improving to approximately 0.6 metres.[31] Operational between July 1963 and June 1967, the KH-7 returned approximately nineteen thousand frames of varying length at a scale of approximately 1:100 000.

The KH-9 Hexagon was a frame camera system that returned imagery from twelve missions conducted between March 1973 and October 1980 and provided better than a fourfold improvement in accuracy and more than a tenfold improvement in spatial resolution over the Argon camera. Over twenty-nine thousand frames, each covering a nominal area of a hundred and thirty by two hundred and sixty kilometres at a spatial resolution of about ten metres, were acquired for mapping, charting and geodesy purposes, with stereo coverage of most areas.

ARCHAEOLOGICAL USE OF SATELLITE INTELLIGENCE IMAGERY

The archaeological potential of photoreconnaissance satellite imagery was recognised long before the Corona material was placed in the public domain. Writing in the Central Intelligence Agency's classified house journal *Studies in Intelligence* in 1977, Robert Poirier, a US photoreconnaissance analyst, described the use of satellite photographs to image a number of Roman sites in Jordan including the legionary fortress at El Lejjun.[32] Known to Western explorers since the latter part of the nineteenth century, the fortress, which dates from around 300CE, was first photographed from the air in the 1930s but was not excavated until the 1980s. Despite the fact that the site has been robbed extensively for stone in the past, the fortress was clearly visible on the satellite photograph, and such details as gates, the U shaped interval towers on the walls as well as some of the internal structure including the ruins of the rows of barrack blocks could be discerned. Although the quality of the original satellite photographs was inferior to conventional aerial photography, it nonetheless demonstrated the archaeological potential.

In his paper, Poirier argued that photoreconnaissance satellite images had great potential for use in archaeological discovery, and that since the US intelligence community did not have the analysis resources to evaluate the mass of imagery collected, photographs should be provided to academia for research use. However, the strict secrecy that surrounded the subject of photoreconnaissance satellites precluded this vision for nearly thirty years. A year after writing his paper, Poirier presented and described an image of the First World War battlefield at Verdun, further illustrating the archaeological potential of photoreconnaissance satellite imagery.[33]

Following the declassification of the Corona products in 1995, their archaeological potential was quickly appreciated, and a growing number of researchers are now using the material in support of archaeological studies (see table overleaf). Whilst still inferior in quality to conventional aerial photographs, the low price and wide coverage makes Corona imagery attractive particularly for areas for which no aerial photographs are available and where maps are either old or small scale.

One of the first users of Corona imagery was David Kennedy of the University of Western Australia, who evaluated KH-4B photographs of the environs of the sites of the ancient Greek and Roman cities of Samosata and Zeugma in the Euphrates valley in Turkey.[47] Samosata had been the capital of allied kings of the Roman Empire, and in the first century CE the kingdom was annexed by Rome to the province of Syria. The city was a flourishing frontier town and housed an entire legion of five thousand soldiers. In the 1990s, the construction of the Atatürk dam on the Euphrates flooded the deserted remains of the city, and whilst a number of archaeological teams carried out small scale

Archaeological applications of declassified US intelligence satellite photographs (Corona)

Location	Mission(s)	Archaeological use	Note
Turkey	1103, 1104	First ever overhead photograph of the Roman city of Samosata on the Euphrates, now totally immersed beneath the Atatürk dam. Downstream of Samosata, Corona imagery was used to assist in the mapping, interpretation and illustration of key places, features and geomorphology in the region of the Roman city of Zeugma prior to flooding of the area following the construction of the Birecik dam	34
England	1104	Investigation of the ability of KH-4B to detect archaeological features in the vicinity of the Iron Age hillfort at Bury Hill, Hampshire. Whilst the upstanding features of the hillfort could be seen, ploughed out features visible on conventional aerial photographs could not be readily discerned	35
Syria	Not specified	Aided geomorphological study of the complex landscape hinterland of the Bronze Age site of Tell Brak	36
Syria	1102, 1108, 1117	Identification of possible archaeological sites in the hinterland of Tell Hamoukar. The photographs were found to be extremely powerful for site identification since they preserve a landscape that is over thirty years old, prior to the expansion of towns, the intensification and mechanisation of agriculture and the introduction of diesel pumps and irrigated cotton fields	37
Syria	1102, 1105, 1108	Identification and mapping of ancient road systems dating from the early Bronze Age in the Upper Khabur basin in northeastern Syria where conventional aerial photography is limited	38
Syria	1108, 1110, 1111	Aided identification of non-Tell settlement remains and distribution and organisation of field systems in Homs region	39
Syria	1038	Provided broader landscape survey as part of an interdisciplinary investigation of an eighth to twelfth century Islamic industrial complex associated with the city of al-Raqqa in northern Syria. Predating both the modern urban expansion of Raqqa and development of extensive irrigation systems in the hinterlands, Corona photographs have proved invaluable for mapping the now largely destroyed cultural landscape	40
Iran	Not specified	Used together with Spot panchromatic imagery to illustrate landscape change on the Susiana plain in southwestern Iran between the late 1960s and early 90s. During this period much of the plain was levelled and an extensive network of irrigation channels constructed which now mask traces of earlier irrigation systems of Sassanian and Islamic date that can be seen as dark lines on Corona photographs	41
Jordan	1115	Used to compare the appearance of features associated with Rome's desert frontier visible on Corona images with conventional aerial photographs of the sites	42
Ukraine	Not specified	Part of a multitemporal, multiresolution database of satellite imagery of Chersonesos, Crimea, an area that is one of the best preserved examples of an ancient Greek agricultural landscape. The site's contemporary strategic position limits physical access and thus remote sensing offers an effective and reliable means of mapping the ancient landscape as well as monitoring urban encroachment over the past thirty years	43
Turkmenistan	Not specified	Used as a dataset within a GIS to investigate settlement distribution relating to evolution of the ancient irrigation system of the river fan of the Murghab delta before the modern building of the Kara Kum canal	44

Location	Mission(s)	Archaeological use	Note
Armenia	1115	Used together with unsophisticated computer hardware and software to identify features including cultivation terraces, stone clearance cairns, enclosures and sites of shepherds' camps	45
Romania	1022	Used in place of large scale background maps for rectification and transcription of conventional oblique aerial photographs covering the Roman site of Micia	46

surveys and excavations, today the site is inaccessible deep beneath the waters of a huge reservoir. In addition to providing the first ever 'aerial' photograph of Samosata, the Corona images used by Kennedy were found to be particularly useful in displaying the principal features of the geomorphology of the region 'in a clear and helpful manner'. Archaeological features associated with the Roman town and city could be identified, although little detail could be discerned. Downstream of Samosata, two large mounds to the north and south of the present day village of Saskan could also be distinguished, as could the course of an ancient 'hollow way' running adjacent to one of the banks of the Euphrates. As with conventional aerial photography of archaeological features, the details of some features in the study area were found to be variable between photographs acquired under different conditions prevailing at different times of year.

Some seventy kilometres to the southwest of Samosata lay the location of the first and only permanent bridge across the Euphrates in Roman times, between the Taurus mountains and Babylonia. The twin towns of Seleucia and Apamea at either end of the bridge were of strategic importance and, like Samosata, received a legion in garrison under Roman rule. For several centuries Zeugma (as the twin towns came to be known) flourished as a fortress city, urban and trade centre and focal point for several key routes between the East and West. The existence of ancient ruins upstream of the modern bridge at Birecik has been known for over two centuries, however like Samosata, Zeugma has now fallen victim to the construction of a new dam, some five hundred metres downstream of the city. Rescue surveys and excavations were conducted by a number of teams, and like the Russian KVR-1000 satellite image used by another team, the Corona photographs used by Kennedy assisted greatly in the mapping, interpretation and illustration of the key places, features and geomorphology of the area.

Subsequent workers have used Corona imagery to investigate a range of ancient landscapes and features in England, Syria, Iran and Jordan (see table). Further archaeological uses of Corona photography in Ukraine, Turkmenistan and Armenia were reported at the 'Space applications for heritage conservation' conference held in 2002,[48] and in a novel use in Romania Corona photographs have been used in place of large scale background maps for the rectification and transcription of conventional oblique aerial photographs. Finally, a recent monograph has made extensive use of Corona imagery in reviewing archaeological landscapes of the Near East.[49] Thus in the very short time since declassification, Corona photography has proved a particularly useful source of aerial imagery for use in archaeological studies.

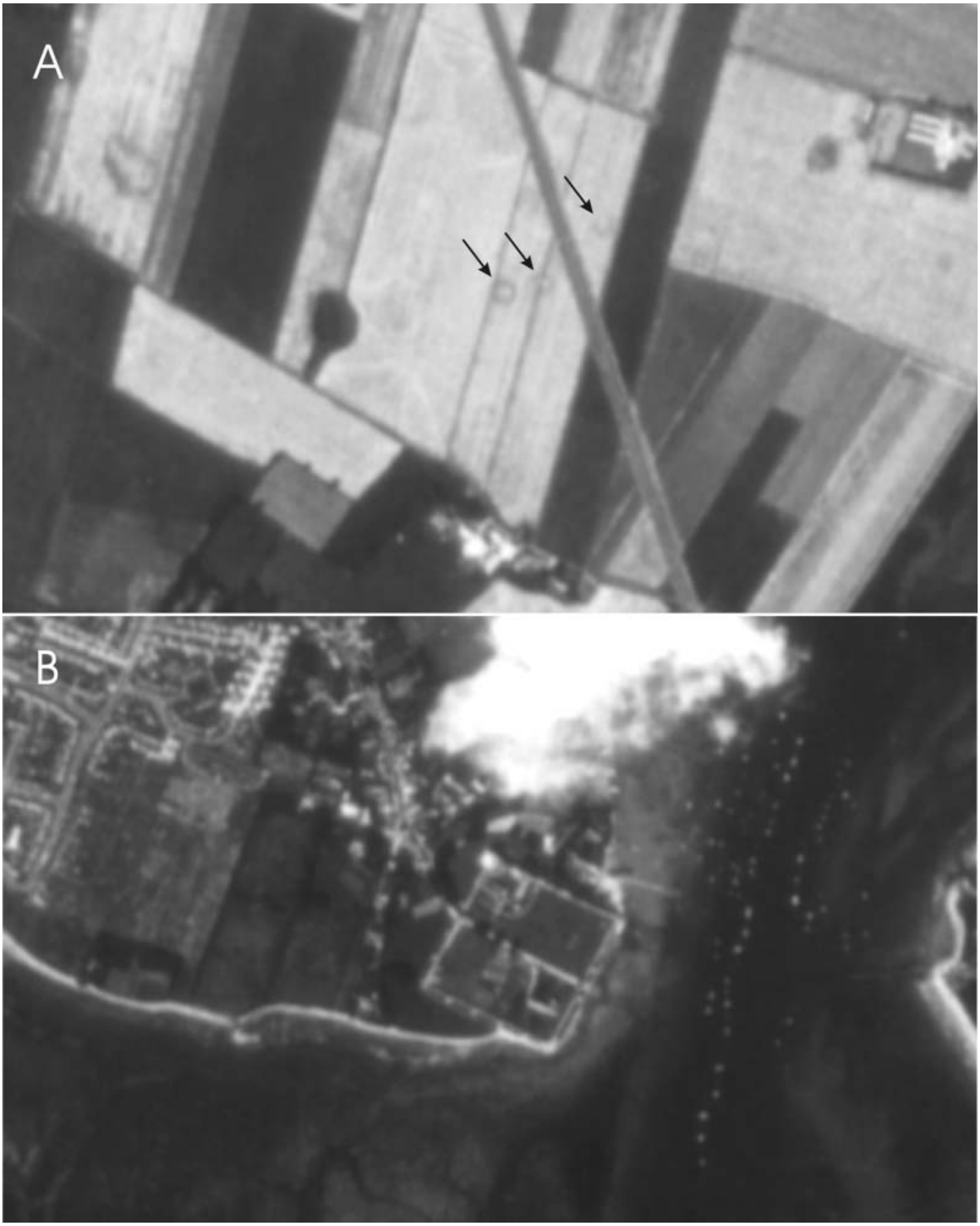
To date, Corona photographs acquired by the high spatial resolution KH-4B system have been used predominantly to detect upstanding archaeological features in the arid regions of Asia Minor and the Middle East, where there is a shortage of conventional aerial photographic cover. However, Corona photography is not limited to the detection of features in relief, and in more temperate regions plough levelled archaeological features can also be detected as crop marks. For example, despite having significant cloud cover, extracts from 1968 KH-4B photography of an area in the vicinity of Fareham in southern England show at least three possible ring ditches visible as crop marks (Fig. 2*a*). These probably represent the ditches of Bronze Age round barrow burial mounds that, through the centuries, have been levelled by ploughing. Although their presence had been suggested on aerial photographs acquired by the UK Ordnance Survey in 1963, the crop marks are bolder on the satellite photograph, suggesting that there is a wider utility for Corona photography in areas in which conventional aerial photographs are readily available. On another photograph acquired by the same Corona mission, the Roman outer wall and bastions together with the Norman keep of Portchester Castle a few kilometres away can be readily seen in relief (Fig. 2*b*), although the quality of the image is significantly poorer than would be the case with conventional medium altitude aerial photography.

In contrast to Corona, the very low spatial resolution of KH-5 Argon photography has constrained its archaeological utility, although as will be seen below it represents a unique source of pre 1970s historical imagery for use in other disciplines. Similarly, the sparse coverage and overall poor photographic quality of the Lanyard product has resulted in no apparent use to date in either archaeological or other studies, and given its very limited geographical coverage it is unlikely to have significant utility in the future.

The archaeological potential of the newly available high resolution KH-7 Gambit photography was investigated by the present author by interpreting an image that included coverage of the former Roman city of Salona, located to the north of the presentday Croatian city of Split on the Dalmatian coast.[50] This particular image was assessed as being broadly comparable with Russian KVR-1000 imagery and clearly shows the remains of the second century amphitheatre together with a number of other features of the Roman city (Fig. 3). Although the archive of Gambit photography is biased towards US Cold War intelligence targets, like Corona it represents an important historical resource that includes coverage of many areas of the globe that are still denied to conventional civilian aerial photography.

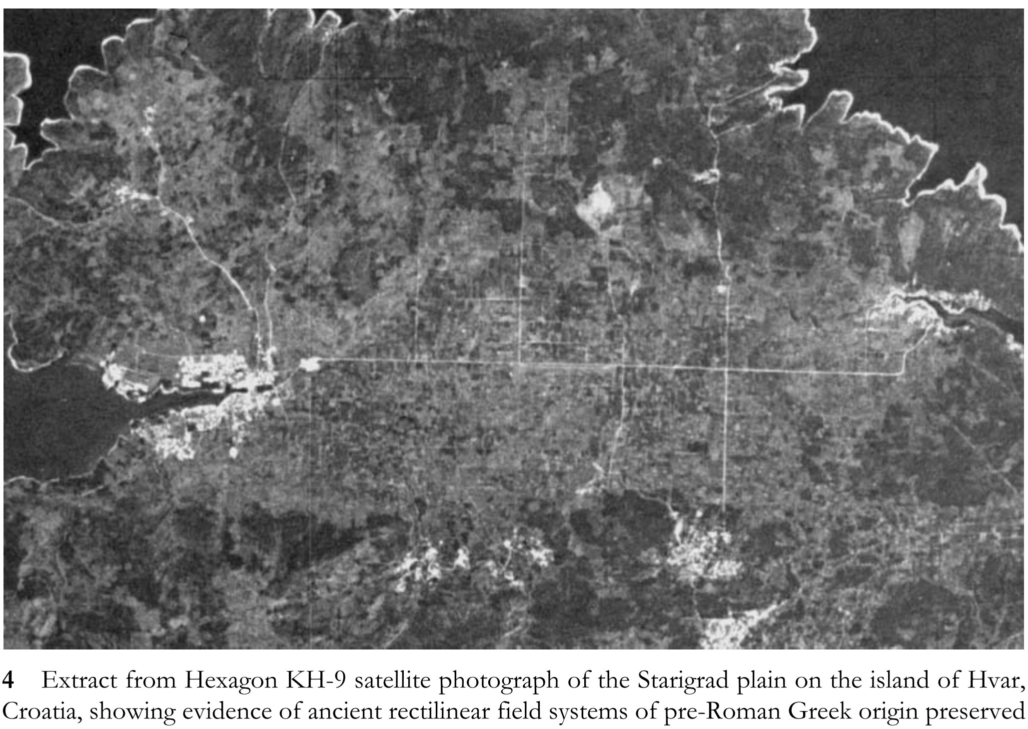
Despite having an inferior spatial resolution to the Corona and Gambit products, relatively large archaeological features can nonetheless be seen on KH-9 Hexagon photographs. A Hexagon photograph covering the island of Hvar in Croatia shows evidence of the remains of ancient rectilinear field systems on the Starigrad plain that are known to date from pre-Roman times (Fig. 4). However, the Hexagon archive is likely to have greater archaeological utility in providing imagery that can be used as background mapping for areas where maps are not readily available or are relatively small scale. In this respect it could be used as a mapping basis for the rectification of higher resolution imagery and conventional oblique aerial photographs with the advantages over Corona photography of the larger area covered by a single image and the absence of panoramic distortion inherent in the Corona camera.

Perhaps the greatest archaeological value of the archive of declassified intelligence satellite photographs is that it represents a unique source of historical imagery from the 1960s and early 70s, predominantly covering areas of the world for which contemporary conventional aerial photographs are not available. It thus has the potential to contain evidence of archaeological features that have since been destroyed through, for example, changes in land use and urban expansion. Furthermore, with the growing recognition that artefacts



2 Extracts from Corona KH-4B satellite photographs showing plough levelled and upstanding archaeological features in southern England: ***a*** crop marks of three possible ring ditches (arrowed) and other features near Fareham, Hampshire. The diagonal feature crossing from top to bottom is the scar of a buried gas pipeline; ***b*** upstanding Roman walls and bastions and the Norman keep at Portchester Castle, Hampshire. Photographs acquired by mission 1104-2 on 17 August 1968 (data available from US Geological Survey, EROS Data Center, Sioux Falls, SD, USA)

3 Extract from Gambit KH-7 satellite photograph showing the destroyed amphitheatre of the former Roman town of Salona, near Split, Croatia. Photograph acquired by mission 4027 on 24 April 1966 (data available from US Geological Survey, EROS Data Center, Sioux Falls, SD, USA)



4 Extract from Hexagon KH-9 satellite photograph of the Starigrad plain on the island of Hvar, Croatia, showing evidence of ancient rectilinear field systems of pre-Roman Greek origin preserved as modern roads and field boundaries. Photograph acquired by mission 1210-5 on 15 July 1975 (data available from US Geological Survey, EROS Data Center, Sioux Falls, SD, USA) and structures dating from the Cold War are worthy of archaeological study,[51] declassified intelligence satellite images could come full circle in providing a unique resource of overhead photography for Cold War archaeologists to exploit in their studies (Fig. 5).

WIDER USES

In addition to use in archaeological prospection, intelligence satellite images have been found to have utility in a number of other scientific disciplines, in particular in studies of environmental change.[52] Low resolution Argon imagery of the Ross ice shelf in Antarctica has been used to reveal large changes in the ice sheet that have occurred in the thirty-five years since the photographs were acquired,[53] and Argon photographic mosaics of Greenland have been used as a means of making quantitative comparisons of changes in ice extent.[54] Corona images have been used to study emissions from the Erta 'Ale volcano in Ethiopia[55] and, together with Argon photography, to reconstruct historical land use and land cover in west central Senegal in order to monitor environmental change over the last thirty years.[56] Likewise, Corona imagery has been used in the Unesco 'Man and the biosphere' programme to monitor land use changes on the Franco-German border.[57] Finally, Corona photography has been used to monitor forest decline in the heavily polluted area that surrounds the Severonikel copper–nickel smelter in the Central Kola peninsula of Arctic Russia.[58] Closer to its intelligence roots, Corona photographs have been used by civilian researchers to locate the detonation point of China's first nuclear explosive test in 1964,[59] as a source of information for studying nuclear proliferation[60] and as a low cost means of generating digital surface models.[61]

5 Course of the Berlin Wall to the south of the city as seen by Corona. The courses of several former railway lines and roads that were blocked by the wall can be readily seen. Photograph acquired by mission 1112-2 on 25 November 1969 (data available from US Geological Survey, EROS Data Center, Sioux Falls, SD, USA)

Whilst civilian multispectral satellite imagery from Landsat and Spot has found extensive use in geological exploration,[62] little use has been made of declassified intelligence satellite photographs in this field apart from a single application of Corona imagery in mineral exploration.[63] This lack of use is probably due to the fact that for the majority of Corona missions, black and white panchromatic film was flown. However, on two KH-4B Corona missions, high resolution colour film was flown experimentally, and whilst at the time it was found to be inferior to standard black and white film for intelligence purposes, it appeared to be well suited to photogeologic mapping where the value of colour greatly outweighed the lower spatial resolution of the product.[64] Unfortunately, copies of these colour images are not readily available, and given the abundance of available civilian multispectral satellite images, it is likely that colour Corona photographs will not be exploited to any significant degree in the future for geological studies.

CONCLUSIONS

At the height of the Cold War in the 1960s and 70s, photoreconnaissance satellites were a key source of strategic intelligence for the USA and its allies. Photographs from the Corona, Argon, Lanyard, Gambit and Hexagon programmes revolutionised the collection of intelligence from the 'denied areas' of the Soviet Union, China and other states from the Middle East to southeastern Asia. Such satellite photographs were used for a variety of analytical purposes, from assessing military strength and estimating the size of grain production, to mapping, charting and geodesy.[65] However their greatest utility was in monitoring the deployment of Soviet strategic forces, and later to verify compliance with arms control agreements thus ensuring that peace was largely maintained between the West and the Soviet bloc and that, ultimately, the Cold War would eventually come to an end.[66]

Thirty years on, intelligence satellite photographs are receiving a new lease of life as a unique source of low cost, fine resolution photographic coverage of areas of the earth's surface in the 1960s and early 70s that are being actively exploited by aerial archaeologists as well as researchers in other fields. Such uses of these intelligence photographs represent vivid demonstrations of Lundahl's 'serendipity effect' of aerial reconnaissance. Given its well proven scientific utility, it is to be hoped that in due course additional high spatial resolution photoreconnaissance satellite imagery will be declassified, thereby adding to this important historical resource of overhead images dating from the latter part of the twentieth century.

ACKNOWLEDGEMENT

The assistance of the Information Access and Release Center of the US National Reconnaissance Office in providing copies of original records relating to the Corona, Argon and Lanyard programmes is much appreciated. This article is dedicated to the surgical and chemotherapy teams at the Royal Hampshire County Hospital, Winchester, UK and to the radiotherapy team at the Royal South Hampshire Hospital, Southampton, UK, who have been instrumental in treating my wife, Yvonne, in her fight against breast cancer.

NOTES

1. D. A. Brugioni: 'The serendipity effect of aerial reconnaissance', *Interdisciplinary Science Reviews*, 1989, **14**, 16–28. This was an unclassified version of a formerly 'secret' article entitled 'The serendipity effect' that

had appeared nineteen years earlier in the Spring 1970 issue of the Central Intelligence Agency's classified house journal *Studies in Intelligence* (declassified 1994, US National Archives and Records Administration, Research Group 263).

2. Because of the highly classified nature of these activities, with the exception of the first generation of satellite systems described later in this review descriptions in the open literature of photoreconnaissance satellite systems are somewhat speculative, but they can nonetheless be considered to be broadly indicative of their capabilities. See for example C. Peebles: *Guardians: Strategic Reconnaissance Satellites*; 1987, San Francisco, CA, Presidio; J. T. Richelson: *America's Secret Eyes in Space: The US Keyhole Spy Satellite Program*; 1990, New York, NY, Harper Collins.
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