Archaeological Prospection
Archaeol. Prospect. (2009)

(www.interscience.wiley.com) DOI: 10.1002/arp.353

Helikite Aerial Photography – a Versatile Means of Unmanned, Radio Controlled, Low-Altitude Aerial Archaeology

GEERT J. J. VERHOEVEN*, JO LOENDERS, FRANK VERMEULEN AND ROALD DOCTER

Ghent University, Department of Archaeology and Ancient History of Europe,
Blandijnberg 2, B-9000 Ghent, Belgium

ABSTRACT During the past 100 years, various devices have been developed and applied in order to acquire archaeologically useful aerial imagery from low altitudes (e.g. balloons, kites, poles). This paper introduces Helikite aerial photography (HAP), a new form of close range aerial photography suitable for site or defined area photography, based on a camera suspended from a Helikite: a combination of both a helium balloon and kite wings. By largely overcoming the drawbacks of conventional kite- and balloon-based photography, HAP allows for a very versatile, remotely controlled approach to low-altitude aerial photography (LAAP). In addition to a detailed outline of the whole HAP system, its working procedure and possible improvements, some of the resulting imagery is shown to demonstrate the usefulness of HAP for several archaeological applications. Copyright © 2009 John Wiley & Sons, Ltd.

Key words: Helikite aerial photography; Helikite; low-level aerial photography; mapping; aerial archaeology; remote sensing

Introduction

In 1908 L.P. Bonvillian took the first photograph from an aeroplane near Le Mans (France), although it was actually one single frame of a motion picture (Newhall, 1969; Doty, 1983). A few years later and largely due to the technological catalyst of World War I, aerial photography from an aeroplane became a standard practice (Deuel, 1973). To date, active aerial photography still largely depends on these manned, heavier-than-air motor-driven aircrafts. In practice, individual archaeologists often acquire their own data from the cabin of a small, relatively low-flying, conventional fixed-wing aircraft, utilizing 135 mm format (or slightly larger or smaller) hand-held still cameras to acquire imagery that is mostly oblique in nature. On some occasions, however, this conventional way of image acquisition is impossible (e.g. forbidden by the military), inconvenient or unsuited to reach particular goals. As an example of the latter, one might think of beyond visible imaging (e.g. ultraviolet photography) or large-scale photography (e.g. 1/250), in which case the forward movement of the aircraft is far too fast to compensate for the situation-specific shutter speed needed.

To deal with these issues and still be able to obtain qualitative imagery, archaeologists often resort to unmanned devices such as balloons,

---

* Correspondence to: G. J. J. Verhoeven, Ghent University, Department of Archaeology and Ancient History of Europe, Blandijnberg 2, B-9000 Ghent, Belgium.
E-mail: Geert.Verhoeven@UGent.be

Received 16 October 2008
Accepted 20 January 2009

kites, model aircraft, blimps and poles to acquire imagery from the air. Generally, these devices allow the (digital) still or video camera to be more or less stationary over specific spots of interest at a particular altitude, which is difficult or impossible to achieve through all kinds of manned aerial platforms such as aeroplanes, powered parachutes, helicopters, balloons, ULMs (ultra légers motorisés)/ultralight aircrafts, gliders and paramotors. As most of these devices have a restricted operation height (e.g. 100 m), they are ideal to perform low-altitude aerial photography (LAAP), also called close-range aerial photography.

The system presented here is a new approach to such low-altitude aerial archaeology, developed in order to acquire highly detailed (digital) aerial imagery on most occasions by means of a Helikite. Before outlining the system, the ground-based approaches mostly used nowadays will be shortly reviewed, as their characteristics will prove essential in showing the advantages of using Helikites.

Low-altitude aerial photography platforms

There are several means used in archaeology and other scientific fields to lift radio controlled (RC) or action-delayed photographic (or video) cameras and acquire large-scale imagery. In general, the following low-altitude unmanned camera platforms are in use to capture low-altitude aerial imagery in archaeology, each with its distinct advantages and drawbacks.

(i) Masts, poles or booms – although these platforms are cost efficient, very portable and stable, they are limited by a moderate maximum operation height of 20 m.

(ii) Unmanned aerial vehicles (UAVs) – encompassing mostly RC model aeroplanes and helicopters, this category is generally characterized by superior navigation possibilities, but problems with induced vibrations, cost and less straightforward operation still allow kites and balloons to be the most widespread LAAP platforms.

(iii) Kites – since the 1970s, kite aerial photography (or KAP) is practised by many individuals and archaeological teams, as these highly inexpensive and portable platforms can accommodate a few kilograms of payload. Moreover, only wind is needed to make it work. This dependency is also its largest drawback, as irregular winds are not suited for KAP and the size of the kite is dependent upon the wind speed. It goes without saying that 'KAPing' is not possible in windless situations.

(iv) Balloons and blimps – these lighter-than-air devices fill in the gap characteristic for KAP, as they can be used in windless and very light wind conditions. Moreover balloon photography is extremely flexible in its setup and operation is easy. However, balloons and blimps become difficult to position and hold steady if the wind speed exceeds approximately 15 km h^{-1}.

Thus it is clear that a combination of a balloon and a variety of kites is often essential to maximize the conditions for low level aerial archaeology. However, rather than using two or more separate lifting platforms (e.g. Whittlesey, 1968, 1974; Aber, 2004; Ahmet, 2004; Bauman *et al*., 2005; Wolf, 2006), a Helikite can be used.

Helikite

The Helikite is a unique design, patented by Sandy Allsopp in 1993 and currently manufactured by Allsopp Helikites® Ltd, combining the two aforementioned constructions. By joining a helium balloon with kite wings (Figure 1), this lighter-than-air device combines the best properties of both platforms. The helium filled balloon allows it to take off in windless weather conditions, whereas the kite components become important in case there is wind: first of all, they lift the construction up in the air to altitudes higher than the pure helium lift. Moreover, the Helikite's lift becomes stronger with increasing wind speed (with an upper lift limit depending on the Helikite's size). Second, the wings counteract any unstable behaviour that is characteristic of balloons and blimps flown in windy

DOI: 10.1002/arp

Figure 1. Inflating the Helikite (photograph by G. Verhoeven).

conditions, hence stabilizing the Helikite (Allsopp Helikites Ltd., 2007).

The Helikite's distinct excellent all-round behaviour has also been reported by researchers of the Centre for Transportation Research and Education (CTRE) at the Iowa State University, who compared the photographic conditions yielded by a kite, blimp, Helikite and balloon in several wind conditions (Figure 2). In this respect, the Allsopp Helikite is not only more versatile than comparable devices, but it supports more payload for its size when compared with ordinary aerostats, and operates in stronger winds than traditional blimps or balloons (Allsopp Helikites Ltd., 2007). Due to the fact that it can be used in adverse weather (e.g. rain, fog, freezing conditions) it is also more flexible in operation than most UAVs.

Based on these properties, a complete photographic system using a 7 m^3 Skyhook Helikite (Figure 1) was designed in 2005–2006 by the Classical Archaeology section of the Department of Archaeology and Ancient History of Europe (Ghent University, Belgium), in collaboration with the Department of Industrial Engineering, KaHo Sint-Lieven, Ghent. For obvious reasons, this type of unmanned photography was termed Helikite aerial photography (HAP).

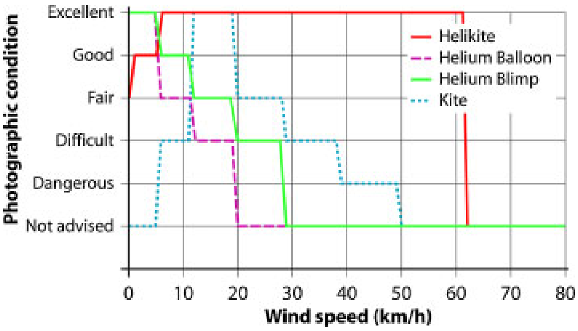

Figure 2. Wind speed versus photographic characteristics for competing alternatives (adapted from CTRE, 2004).

Helikite aerial photography

The system

The requirement was to allow the acquisition of general overviews as well as highly detailed images of specific locations, both in the visible and invisible range of the electromagnetic (EM) spectrum, so this complete system had to be stable, easily maintained and remotely controllable. In this section, the nine major components that are part of the finally assembled HAP system are described separately (and indicated on Figure 3).

The camera-lifting device is a 7 m^3 Skyhook Helikite that can lift a mass of about 3.5 kg in windless conditions at ordinary air pressure and

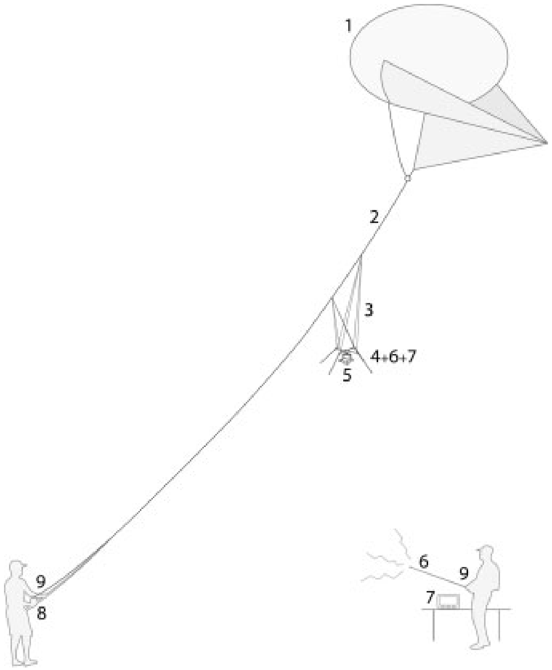

Figure 3. The complete Helikite aerial photography system (illustration by G. Verhoeven).

temperature. Due to its wings, a 25 km h^{-1} wind allows for a buoyancy of 100 N: i.e. 10 kg of payload. This value largely surpasses the gross lift of pure helium (He). With a gaseous density d of 0.18 g L^{-1} (or 0.18 kg m^{-3}) at 0°C and 1 atmosphere (i.e. standard temperature and pressure: STP) – compared with 1.29 kg m^{-3} at STP for air (Zumdahl, 1997; Silberberg, 2006; Messer Group GmbH, undated) – 1 m^3 helium lifts at STP slightly more than 1.1 kg (= 1.29 kg m^{-3}– 0.18 kg m^{-3}) of payload, a value that will alter with varying temperature and atmospheric pressure (Cuneo, 2000). Consequently, a 7 m^3 airship can have a maximum buoyancy of about 77 N (if its own mass was zero). However, the design of the Helikite overcomes the physical restraints of its lifting gas. By way of comparison, Aber (2003) mentions a helium blimp of 7 m^3 with a net lift of 2.3 kg, whereas Summers (1993) utilized a 20 m^3 helium blimp, yielding 95 N net buoyancy. Table 1 gives an overview of the current (April 2008) Allsop elikite product line, with the model specific (lifting) capabilities indicated.

To securely fly the Helikite, an appropriate tether must be used, taking several considerations into account. First of all, higher flying (i.e. above 100 m) causes sag of the line due to gravity. Therefore, the tether's mass is best kept to a minimum. Additionally, the line is also not allowed to stretch too much (certainly not when 300 m of line is used to reach maximum operation height), as the combination of both sag and stretch will make it very hard to keep tight control over the Helikite. Therefore, Dyneema®, an extremely strong polyethylene fibre, is advisable (Bults, 1998), as it has only 5% stretch and is more than ten times stronger than steel per unit of weight (DSM, 2008). With a high breaking strain of 270 kg and a diameter of only 2.2 mm, the currently employed Dyneema® tether allows the Helikite to fly securely and makes steering easy, as the operator can readily feel the connection with the Helikite. in order to attach the Dyneema® line to the Helikite knots are inevitable. However, together with kinks or angles, knots stress the fibres of the tether unevenly, weakening the strength of the line. The degree of strength loss is largely knot dependent (Leffler, 1999), with particular knots weakening the line to about 50% of its rated strength. It is therefore safe to assume that the tether will never perform at more than half its claimed breaking strain (Richards, 2005; Grog LLC, 2007). Hence, 270 kg Dyneema® is still safe as a tether. Ideally, 500 kg Dyneema® line should be used, as resistance to abrasion also needs to be taken into account. However, its mass and diameter would compromise the payload capacity too much in windless conditions and create problems with the amount of flying line that can be held by the reel (Figure 3(8)).

The camera rig is attached to the tether some 20 m below the Helikite (to avoid vibration effects and sudden movements of the Helikite), and consists of a camera-supporting frame or cradle and a suspension system. The Picavet

Table 1. Helikite models and performance (adapted from Allsopp Helikites Ltd., 2007)

Helikite type	Helium capacity (m^3)	Material thickness (inch × 10^{-3})	Lift in no wind (kg)	Lift in 15 mph wind speed (kg)	Approximate maximum wind speed (mph)	Approximate maximum unloaded altitude (ft)	Helikite length (ft)
Vigilante	0.15	1	0.03	0.15	25	1000	3
Lightweight	0.15	1	0.06	0.18	25	1300	3
Skyshot	1.6	2	DSC	DSC	30	2500	6
Skyhook	1.0	2	0.3	1.5	28	2000	5
Skyhook	1.6	2	0.5	2.5	30	2500	6
Skyhook	2.0	2	1.0	4.8	32	5500	7
Skyhook	3.3	3	1.2	6.5	35	6000	9
Skyhook	6	3	3.0	9.0	40	6500	11
Skyhook	11	3	5.5	12.0	45	9000	12
Skyhook	16	3	8.0	16.0	46	9000	13
Skyhook	25	6.0	9.0	20.0	50	9000	16
Skyhook	35	6.0	14.0	30.0	60	11 000	22
Skyhook	64	6.0	30.0	70.0	70	15 000	26

suspension applied in this system allows for self-levelling and securing the cradle. Named after its French inventor, the Picavet suspension system (Picavet, 1912) can be applied in several variants (Beutnagel *et al.*, 1995; Hunt, 2002). The one used in this project is a large rigid cross (known to be more twist resistant than small crosses – Gentles, 2007) with each of the four ends (Figure 4 (1–4)) connected at two anchor points (Figure 4 (A and B)) to the flying line. The latter is accomplished by means of a double pulley block, combined with a dedicated fishing hook that is attached to the line by means of a Brooxes Hangup^{TM}. The small Ron Thompson DynaCable line (a micro-filament fishing line of 0.25 mm diameter and a 20.2 kg breaking strength) that provides this connection is one looping string. Lastly, a ring constrains the two innermost crossing cables. The result is a simple, very lightweight dampened suspension for the cradle, superior to the often used pendulum (Beutnagel *et al.*, 1995), and capable of minimizing camera swinging when manoeuvring (which changes the angle of the tether) as well as absorbing all kinds of vibrations (e.g. those induced by the wind), the latter being one of the prime requisites for convenient LAAP (Ebert *et al.*, 1997).

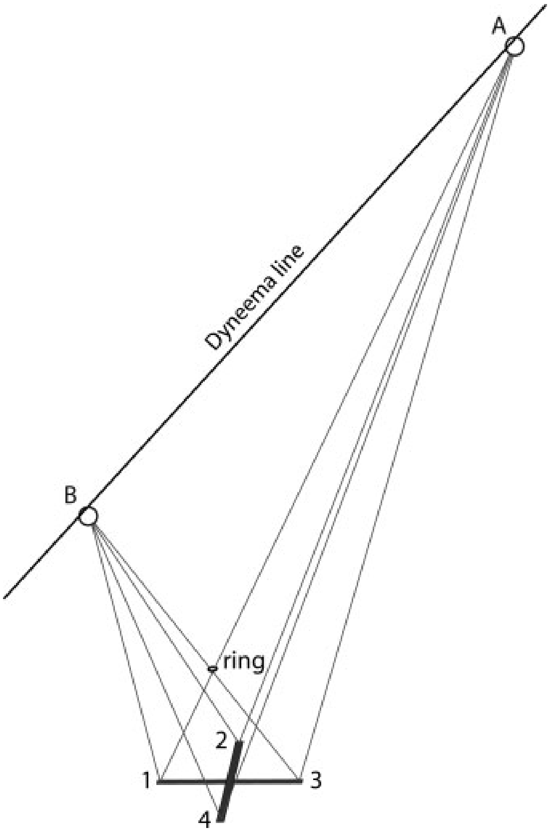

Figure 4. The Picavet suspension (illustration by G. Verhoeven).

The sturdy aluminium and carbon cradle, the camera supporting part of the rig, was specifically designed and built by J. Loenders within the framework of his master's thesis. Except for the four carbon legs and the carbon Picavet cross – allowing the construction to stand and take-off independently and protect the still camera in case of a rough landing (Figure 5A) – the cradle is completely made of aluminium: a cheap, light, but sturdy, bendable and easily drilled material that is often used to construct cradles (Eisenhauer, 1998). Due to its design as well as the solid, precisely lasered and aluminium frame profiles used, the cradle experiences a very low static nodal stress when loaded (Loenders, 2006), allowing for extremely fluid rotations, the latter controlled by three small servo motors (type Graupner C577). Although existing cradles come in all kinds of designs (Eisenhauer, 1996; Hanson, 2001), many of them, certainly the older ones, only allow the camera's orientation to be set before taking it aloft. The more advanced ones enable remote control of the attitude of the camera, generally allowing for rotation (0°–360°) and tilt (0°–90°). However, altering the camera's orientation with only two degrees of freedom (DF) will always exclude certain combinations of view. Hence, this cradle was designed as to allow for three remote controlled DF of the camera (see Figure 5B): $\omega = -45^\circ$ to $+45^\circ$ around X (tilt or roll), $\varphi = -45^\circ$ to $+45^\circ$ around Y (tip or pitch) and $\kappa = 0^\circ$ to 360° around the Zaxis (swing or yaw, but also called pan in this context). By implementing these three functions both vertical and oblique pictures can be taken, the latter with every possible orientation in relation to the object/site under investigation and/or position of the Sun. Even though still a prototype, the current cradle largely fulfils the initial design goals, as it is durable, easily operated, and steady with smooth rotations at the joints.

The cradle was designed to allow a variety of cameras to be mounted, but not more than one simultaneously. Although the initial testing was

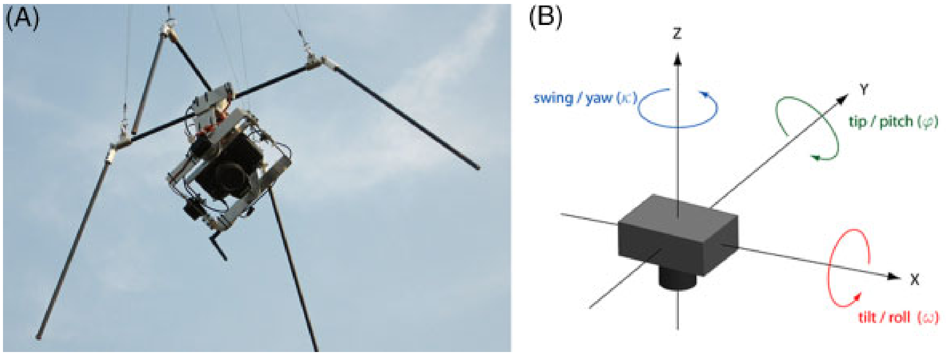

Figure 5. (A) The cradle (photograph by W. Gheyle), which allows (B) the camera to tilt, tip and swing (illustration by G. Verhoeven).

performed using a film-based Nikon F70 single-lens reflex (SLR) camera, all currently cradle-mounted cameras are digital still cameras (DSCs) of the SLR-type: the Nikon D50$_{NIR}$, D70s and D80$_{FS}$. Whereas the first SLR is a converted Nikon D50 that allows only true near-infrared (NIR) photographs to be taken (Verhoeven, 2007, 2008b; Verhoeven *et al.*, 2009), the full spectrum (FS) modified Nikon D80 enables NIR, visible and near-ultraviolet (NUV) photography (Verhoeven, 2008a). The Nikon D70s is a conventional DSC, which is used to acquire 'normal' visible photographs. To trigger the shutter of these SLRs, a gentLED is used. When connected to a RC receiver, these tiny devices can be triggered by the latter to emit infrared (IR) signals that can operate digital still and video cameras with IR receivers (Gentles Ltd, 2007). As all aforementioned digital SLRs (D-SLRs) contain such a wireless receiver, they can be operated remotely by a gentLED SHUTTER (only one of the several gentLED options) to enable focusing and releasing the shutter. Moreover, D-SLRs suspended from the Helikite have many advantages: they are lightweight (620 g, 679 g and 668 g respectively, batteries included), there is no restriction to 36 frames, the exposure can be calculated automatically (with aperture or shutter speed priority), and a wide choice of lenses with different focal lengths is available (at a range of qualities and prices); all four are essential features for convenient RC photography (Fosset, 1994).

To control the shutter and enable the steering of the camera, a six-channel proportional RC hand-held transmitter (type Graupner X-412 UNIT 35 MHz – Figure 6) uses radio signals of 35 MHz to wirelessly send the commands given by the operator to a proportional six-channel receiver (type Graupner R700 miniature SUPERHET) mounted on the cradle. This receiver, for its part, controls the three small Graupner servo motors to make the camera rotate in all possible directions, while a fourth receiver channel is used to trigger the gentLED and allows the DSC to focus and take a photograph.

Being unable to directly observe the area photographed is one of the greatest disadvantages of certain close range aerial photographic solutions (Harding, 1989), as it is very hard to estimate what the still camera will exactly photograph (Heafitz, 1992). To counteract this, a direct video link was established using the Pro X2. This very handy plug and play video system

Figure 6. Steering the digital still camera by assistance of the live video link (photograph by W. Gheyle).

consists of: a tiny 4.8 V Hi Cam EO5-380 CCD camera ($W \times H \times D = 30\,mm \times 25\,mm \times 28.6\,mm$) attached to look directly through the camera's eyepiece; a connected micro FM (frequency modulation) transmitter to send the video signal wirelessly to the ground; a ground-based audio/video receiver with a patch antenna (8 dBi) to pick up the signal and feed it to a small monitor (1440 pixels × 234 pixels). In this way, the TFT (thin film transistor) screen, which runs on a 12 V battery, instantaneously displays the area seen by the camera-lens combination (Figure 6), allowing the camera operator(s) to correctly orientate the D-SLR, compose the shot and decide whether or not to take the image. Moreover, as the viewfinder display also shows useful information on the focus, the number of exposures remaining, the battery status, aperture and shutter speed, the camera operators can check the DSC's normal operation and verify when the memory card is full. Thanks to its compactness and low mass (about 65 g, excluding the 4.8 V battery needed to feed both the video camera and transmitter), the Pro X2 system is ideal for RC aerial photography. Moreover, the 2.4 GHz transmitter's output power of 200 mW allows the video signal to be sent over about 300 m line-of-sight (Hi Cam, 2005).

One can imagine the tractive force of the Helikite when flying even in moderate winds. Using a big-game fishing lever drag reel (type Shimano Tiagra™ 80W) and accompanying carbon sea-fishing rod (type Shimano Tiagra™ Trolling 80AX), these forces can be managed reasonably well and allow the Helikite's operator (i.e. the 'navigator') to freely walk around while letting out tether smoothly and quickly, using the rod to guide the line. Fixing a large and solid winch to the ground could be more convenient to pull down the Helikite, but severely restricts steering and risks the penetration of archaeological layers. With a mass of 3.2 kg, a large winder handle and a two-speed gear ratio (1/2.5 to take in line fast and 1/1.3 for high power retrieves, a feature that is essential for flying kites/Helikites – Eisenhauer, 1995), this reel is capable of holding at least 300 m of the specified Dyneema® line. When the spool is completely filled, the reel's maximum drag is about 18 kg and therefore sufficient to operate in winds of at least 30 km h^{-1}. The reel's construction also counteracts the faster winds that can be expected at higher altitudes, as its drag increases with reduced line level. In practical terms, the reel's drag force will be doubled to some 36 kg when approximately 225 m Dyneema® line (about 75% of the full spool) is off the reel, although these figures should not be followed too strictly, as many external factors can affect drag performance (Shimano®, undated). This means the reel can always be slowed down and even stopped completely by the Helikite's navigator, as 35 km h^{-1} is determined to be the maximum ground wind speed to safely and conveniently perform HAP – hence covering about the same operating range as a kite and blimp combination. The fishing rod and reel are attached to the navigator's body using a big-game fishing harness and a Tsunami™ TS-A-1 Gimbal Utility Belt (Figure 7). Although this combination is primarily designed to allow the body to deliver maximum pulling leverage when the rod is drawn downwards – rather than upwards as is the case in HAP – it is still very useful when walking around, pausing or reeling in the Helikite, as the rod will always rest in the gimbal belt, while the shoulder harness makes sure the reel and rod stay securely attached to the navigator's body in every situation.

As a fast running tether (and even Dyneema® line under tension) can severely cut exposed skin, gloves are of the utmost importance. Therefore, both the navigator and the persons assisting in attaching the cradle to the tether (generally the

Figure 7. Fishing rod and reel attached to the navigator's body (photographs by W. Gheyle and D. Van Limbergen respectively).

camera operators), always wear Marigold Industrial Kevlar handgloves (FB20PD).

The combination of all these nine elements forms the complete HAP system.

Cost, maintenance and operation

Apart from the initial purchase cost of the Skyhook Helikite with accompanying Dyneema® tether (circa € 4000), the fishing gear (€ 1350) and the Pro X2 (about € 550), the price tag of other necessary parts (such as TFT screen, servos, RC transmitter, batteries, flight case, gloves, etc.) was very moderate. In the end, the building of the complete HAP system – with its prototype aluminium cradle – was about € 8000. Besides being affordable, HAP's running costs are low, because all equipment is driven by rechargeable batteries and the construction is very cheap to maintain. As the buoyancy comes from helium (He), the only additional cost when applying HAP is the need for this completely inert, non-toxic, colour-, taste- and odourless noble gas. The non-flammable helium is transported in a pressurised B50 cylinder containing 10 m^3 of this gas, priced at about € 150 (+ additional rent for the cylinder). Once inflated, the Helikite only needs to be topped up with a minimal amount of helium twice a week. As a result, one B50 cylinder proved to be largely sufficient for one month of HAP over one area. When different locations have to be photographed, a delivery van is rented to store the Helikite partly deflated and transport it to the area of investigation, as it is not feasible to recover the helium from the balloon in the field, while completely refilling a 7 m^3 Helikite daily would be too expensive. In practice, one week of intensive HAP (on six different sites) was completed with only one 10 m^3 volume cylinder. To cut down costs further, the purchase of a large trailer that enables the storage of the whole, inflated system is considered. Moreover, the trailer could act as a protective hangar. As a Helikite crash is almost out of the question, additional expenses due to broken equipment can largely be prevented.

To apply HAP in practice, the Helikite is first inflated to its desired pressure using a tapered foil filling outlet mounted onto the helium cylinder and slid into a plastic plug, which is connected to the Helikite's non-return valve. Afterwards, the DSC and lens are mounted onto the cradle and all mechanisms thoroughly checked twice. Once the maximum wind speed is verified with a hand-held anemometer and the Dyneema® line attached to the Helikite using a karabiner, the Helikite operator attaches the reel and rod to his/her body by means of the harness. When the aerostat is sent skyward, the RC transmitter and receiver as well as the Pro X2 are activated and tested once more by the camera operator(s). As soon as the Helikite is about 20 m aloft, the rig is attached to the tether and finally more line is let out to send the complete system skyward. To avoid any punctures in the Helikite's delicate surface, all aforementioned operations take place on a large and thick canvas.

Once the system is completely and safely airborne, the Helikite's navigator walks around to establish the correct position and height for image acquisition, while at least one camera operator (preferably two) determines the DSC's angle and decides to ultimately shoot the aerial imagery. Constant communication and co-ordination between both teams is enabled by two-way radios and is deemed absolutely crucial for accurate positioning of the camera, flight planning and signifying the presence of power lines and potential conflicts with occupied aircraft; an issue not to be taken too lightly (Benton, 1998a,b) and demonstrating the crucial need for this second camera operator. Finally, some training and experience are vital to yield above-average results and to make sure efficiency and reliability in image acquisition remains constantly high.

Possible improvements and drawbacks

Even though HAP completely meets most points identified by Walker and De Vore (1995) and Schlitz (2004) for effective LAAP (i.e. low velocity, small take-off and landing space, portability, low cost, minimal operational staff, low vibration, reliable power supply, fast to set up and employ, low risk and low impact) and its advantages over conventional kite and balloon

DOI: 10.1002/arp

photography are evident, the system is not perfect. Aerial imagery with a high spatial and temporal resolution can be generated in several wind conditions, but the camera cradle is not (yet) fully weather proof, making it impossible to use in case of rainfall (although one can doubt the usefulness of aerial photographs taken during such wet conditions).

Second, as walking the Helikite around and allowing it to ascend or descend to various altitudes is the only way this aircraft can be moved into position, it remains rather challenging to accurately establish a precise camera location and/or take photographs along a previously outlined track – a problem encountered with all forms of photography using kites and blimps (Myers and Myers, 1980; Karras *et al.*, 1999; Tielkens, 2003; Skarlatos *et al.*, 2004). Currently, the position of the D-SLR is largely determined by looking both at the Helikite's location and the transmitted video image on the ground-based monitor; by passing the required instructions (i.e. higher, lower, left, right) on to the navigator, the latter decides how to move with the Helikite – taking the direction of the wind and local topography into account – in order to move the DSC to where it should be. This approach has already proven to be a very convenient way of working. However, in cases where ground conditions are very monotonous (e.g. a very extensive corn field), the camera operators will struggle to be properly oriented. In an attempt to counteract such issues (and improve the positioning in general), the signal of a very small, cradle mounted GPS receiver with WAAS/EGNOS (Wide Area Augmentation System/European Geostationary Navigation Overlay Service) capabilities will in the near future be transmitted to the ground. Its accuracy of geolocation, about 3 m at 2σ RMSE (root mean square error), should be very helpful in establishing the required geodetic position of the DSC, whereas the complete flight path (which is continually logged) will be available afterwards to geocode the photographs and visualize the camera's three-dimensional position through time.

Third, the possible places of survey can be limited by objects that may conflict with the tether: trees, high-tension power lines, houses, scrub, etc. Furthermore, there must be a suitable place for the operator to stand for the desired shots given the specific direction of the wind, the length of the tether and general topographic setting. Consequently, the positioning capabilities of UAVs still remain superior for RC LAAP.

Finally, the helium dependency might in some situations be the largest drawback: besides its cost, it might not always be possible to purchase helium locally and obtain it afterwards on site; in some situations, this can be a reason not to opt for such helium-filled devices (e.g. Allen, 1980; Owen, 1993; Asseline *et al.*, 1999). Some authors, however, point to the advantages that helium allows for very silent operation and the vehicle to be aloft for extended periods of time (Marks, 1989), and Aber (2004) favoured helium blimps over hot-air blimps due to reasons of field operation and handling, dimensions and cost.

Archaeological applications

Notwithstanding some inevitable drawbacks, HAP photography has been rigorously tested since 2006 and proved to be a very stable, easily maintained and versatile radio controlled system. From 2007 onwards, a large amount of low-altitude archaeological image data has been generated at several geographical locations in varying weather conditions. Although HAP was initially developed to allow for analogue NIR site photography (Verhoeven and Loenders, 2006), its application became much wider and now allows for various types of aerial archaeological applications.

General overviews and small area reconnaissance

With a maximum operating altitude limited – for the moment – to about 200 m, a vertically oriented DSC can record approximately 240 m × 160 m when fitted with a 20 mm lens, yielding a scale of 1/10 000. If some obliqueness is allowed, the area captured can be much larger. Such oblique angles are suited to the overview of a large site and/or its direct environment. If climatic and environmental conditions are

Figure 8. *Decumanus maximus* leaving the western gate of the Roman town *Potentia*, discovered by small-area reconnaissance based on Helikite aerial photography (HAP with Nikon D70s + Nikkor 20 mm f/3.5 AI-S).

favourable, these overviews can also yield new archaeological information, as was the case in Figure 8. When acquiring imagery to illustrate the direct relationship between the Roman mausoleum (1) and the western gate (2) of the Roman city *Potentia* (Adriatic Italy, Regione Marche), the trajectory of the *decumanus maximus*'s *extra muros* prolongation became largely apparent as a very distinct negative crop mark. Given the fact that this feature had previously been unnoticed in the grassland, two new conventional reconnaissance flights were initiated. Hence, HAP also gave clear indications about the information one could expect when stepping into a small aeroplane. The latter method thus still remains mandatory because – just like all unmanned systems but the very heavy, military based UAVs – HAP is impractical for surveying geographically extended areas.

Figure 9. Near-infrared photograph of *Potentia*'s temple area (HAP with Nikon D50$_{\mathrm{NIR}}$ + Nikkor 20 mm f/3.5 AI-S).

Site overview for documentation and interpretation

On a much larger scale (ca. 1/500 to ca. 1/5000), highly detailed overviews of archaeological sites can be produced (Figure 9), imagery that can suit several purposes: documenting the progress of ongoing excavations and the several field phases (e.g. the different layers excavated), generating imagery to use in presentations, folders and books, revealing minute aspects about individual features that cannot be seen in plans or from traditional images as well as aiding in the interpretation of a site. In case the site is too extensive to be caught in one frame, a combination of overlapping photographs can be used to generate site-encompassing mosaics (e.g. Ahmet, 2004; Owen, 2006). Thus, HAP bridges the gap between the lowest conventional aerial photography and the highest ground supported pole photography. Although one could acquire such imagery without a live video link, the ability to see what the D-SLR will capture is a very welcome means in establishing a cost-efficient workflow, because it allows the operators to frame and compose in a convenient way instead of shooting dozens of frames approximating a workable image of the subject under consideration.

Site mapping and photogrammetry

Even though such close range photographs may not always result in plans, HAP is well suited to the acquisition of stereophotographs to subsequently generate topographic surfaces and accurate planimetric information by means of photogrammetry – the latter process already being explored since the nineteenth century (Birdseye, 1940). In a similar way, stereoscopic photography has already been performed several times with kites, blimps and balloons (e.g. Whittlesey, 1968, 1970; Chagny, 2001). Although there are people that fly stereo camera rigs (e.g. Schenken, 1997; Aber *et al.*, 2002), the baseline provided by these constructions is often too small to yield stereo imagery for precise height measurements (Becot, 1998). Therefore, the mono-DSC of the Helikite has to be moved from one point to another, so as to generate multiple stereo image pairs with a certain overlap. In order to generate complete excavation plans or intrasite maps as smoothly as possible, the cradle is set to acquire (near) nadir photographs (i.e. vertical). Because the appropriate ground control points (GCPs) – marked prior any excavation and measured by a total station survey – must be incorporated into the imagery (Figure 10), such very low-altitude mapping needs rather precise framing (Bollinger, 1995), making the live video link a necessity. However, the end products will allow the generation of maps much faster and more consistently than most other, low-cost techniques (Horton, 1994), and the textural and colour information provided by the ortho-images remains essential to complement expensive three-dimensional laser scanning (Shaw and Corns, 2008). This way, HAP is consistent with the view of Żurawski, who stated that all ongoing excavations should have a 'handy, reliable and inexpensive vehicle capable of shooting aerial pictures at a particular moment of the fieldwork' (Żurawski, 1993, p. 244). The fact that this approach is not restricted to conventional sites has been illustrated by several scholars, who used similar unmanned lighter-than-air constructions to map underwater remains (e.g. Whittlesey, 1970, 1974; Jameson, 1976; Myers and Myers, 1985).

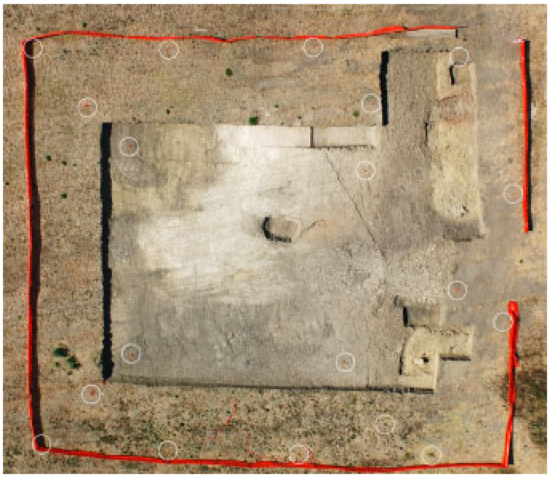

Figure 10. Near vertical photograph of an excavation area with ground-controlled positions indicated (HAP with Nikon D70s + Nikkor 20 mm f/3.5 AI-S).

Monitoring

Due to its ability to generate imagery with an extremely high temporal resolution (i.e. the ability of a system to record images at a certain time interval – e.g. one day versus one month), a fast response to events and detailed site-based monitoring at short time intervals is possible with HAP (Figure 11). As an example, one could base a flying strategy on the outcome of such multi-temporal, sequential data: as soon as the first crop marks start appearing in the HAP imagery over a known crop-mark-sensitive site, the urgency to begin conventional reconnaissance flights can be registered.

Multispectral sensing

Being a stable system, HAP is suited for those situations where long shutter speeds are inevitable: low light conditions, narrow-band and non-visible remote sensing. As previously mentioned, the initial aim in developing HAP was to perform close range, film-based NIR photography (Verhoeven and Loenders, 2006). However, it soon transpired that digital NIR photography is far less cumbersome, with much shorter exposure times compared with the analogue technique (Verhoeven, 2008b). As an example, Figure 12B shows a NIR record of a tower and connected piece of wall belonging to the central Italian Roman city of *Septempeda*, and Figure 12A displays a conventional aerial photograph of the same location, taken one day later but with the anomalies imaged in a less distinct way.

DOI: 10.1002/arp

Figure 11. Monitoring several excavation phases (HAP with Nikon D70s + AF Nikkor 50 mm f/1.8D).

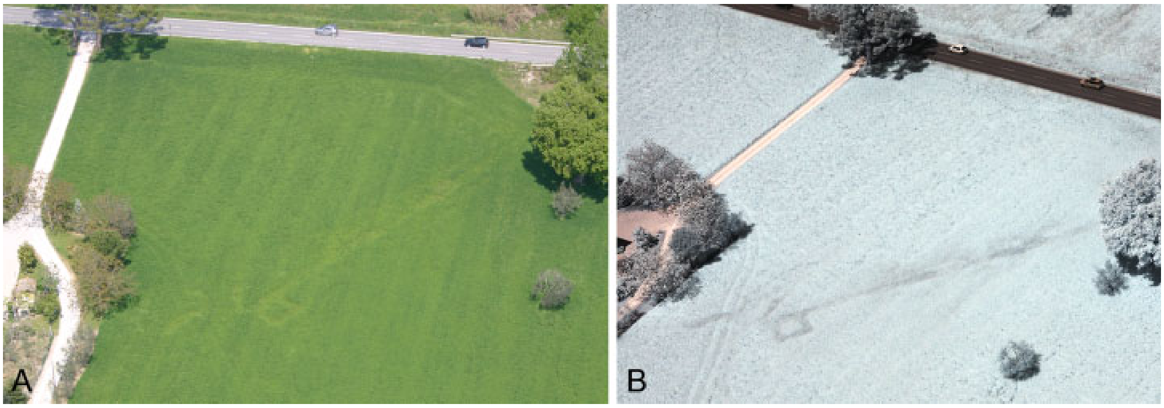

Figure 12. (A) Visible (photograph by F. Vermeulen) and (B) pure near-infrared record (HAP with Nikon D50$_{NIR}$ + Nikkor 20 mm f/3.5 AI-S) of a Roman town wall and connected tower.

Since the summer of 2008, the Helikite-based system has also been applied as a research instrument for digital NUV photography by means of a modified Nikon D80 (Verhoeven, 2008a). The same D-SLR will also be used in the near future (i.e. summer of 2009) to explore narrow-band photography, together with NUV imaging aimed at better revealing subsurface structures.

Conclusions

Fitting a (modified) DSC to a Helikite allows for low-level photography during conditions in which a tethered balloon or a kite would fail to work properly. By holding a 7 m^3 unmanned, helium-filled Helikite aloft with a tether, different low-level aerial photographic methods can be used as the device is largely scale-independent. Although the solution is not perfect, HAP enables photography at particular times of the day, in varying weather conditions, is uncomplicated to deploy, has a large range of operation altitudes and is easy to maintain. Hence, it is often more cost effective and flexible than other individual approaches in yielding high spatial and temporal resolution coverage.

Acknowledgements

This paper arises from the first author's ongoing PhD, which studies the application of remote sensing in archaeological surveys. The research is conducted with permission and financial sup-

DOI: 10.1002/arp

port of the Fund for Scientific Research - Flanders (FWO) and supervised by Professor Frank Vermeulen (Department of Archaeology and Ancient History of Europe - Ghent University). The development and construction of the HAP system benefited greatly from a generous grant afforded by the UTOPA Foundation (Voorhout, The Netherlands). The authors also owe much to the collaboration of Devi Taelman and Dimitri van Limbergen, who proved to be essential as camera operators. Finally, Wouter Gheyle is acknowledged for taking pictures when testing the Helikite.

References

Aber JS. 2003. Applications of small-format aerial photography in North Dakota. *North Dakota Geological Survey Newsletter* **30**: 16–19.

Aber JS. 2004. Lighter-than-air platforms for small-format aerial photography. *Transactions of the Kansas Academy of Science* **107**(1–2): 39–44.

Aber JS, Aber SW, Pavri F. 2002. Unmanned small-format aerial photography from kites for acquiring large-scale, high-resolution multiview-angle imagery. In *Integrating Remote Sensing at the Global, Regional, and Local Scale. Proceedings of Percora 15, Land Satellite Information IV and ISPRS Commission I Conference*, 10–15 November 2002, Denver (volume 1).

Ahmet K. 2004. The Western Papaguería from the Air: digital imagery using kite and balloon aerial photography. In *Enter the Past. The E-way into the Four Dimensions of Cultural Heritage. CAA 2003. Computer Applications and Quantitative Methods in Archaeology, Proceedings of the 31st Conference*, Magistrat der Stadt Wien, Refereat Kulturelles Erbe, and Stadtarchäologie Wien (ed). Archaeopress: Oxford; 46–49.

Allen J. 1980. Lift off. *Popular Archaeology* **2**(3): 25–27.

Allsopp Helikites Ltd. 2007. *Allsopp Helikites. The World's Most Advanced Lighter-Than-Air Aerostats*. www.allsopphelikites.com (date of access: 13 January 2008).

Asseline J, De Noni G, Chaume R. 1999. Note sur la conception et l'utilisation d'un drone lent pour la télédétection rapprochée. *Photo interprétation, images aériennes et spatiales* **37**: 3–13 and 42–47.

Bauman P, Parker D, Goren A, Freund R, Reeder P. 2005. Archaeological reconnaissance at Tel Yavne, Israel: 2-D electrical imaging and low altitude aerial photography. *CSEG Recorder* **30**: 28–33.

Becot C. 1998. Accurate stereokap. *The Aerial Eye* **4**: 8–9 and 18.

Benton C. 1998a. Kites vs. Aircraft. *The Aerial Eye* **4**: 4–45.

Benton C. 1998b. Towards safer kaping. *The Aerial Eye* **4**: 10–11 and 21.

Beutnagel R, Bieck W, Böhnke O. 1995. Picavet – past & present. *The Aerial Eye* **1**: 6–67 and 18–19.

Birdseye CH. 1940. Stereoscopic phototopographic mapping. *Annals of the Association of American Geographers* **30**: 1–24.

Bollinger R. 1995. Using aerial micro-video. *The Aerial Eye* **1**: 16–17.

Bults P. 1998. What's my line? *The Aerial Eye* **4**: 6–7.

Chagny B-N. 2001. La photographie stéréoscopique, prise de vue sous cerf-volant et visualisation des clichés. *Le Lucane* **96**: 17–23.

CTRE. 2004. www.ctre.iastate.edu/research/remote/Helikite/Presentation(c).ppt (date of access: 24 February 2006).

Cuneo P. 2000. The physics of lifting gases. *Gas Division Newsletter* **1**: 5–6.

Deuel L. 1973. *Flights into Yesterday. The Story of Aerial Archaeology*. Penguin Books: Ringwood.

Doty RM. 1983. Aloft with balloon and camera. In *The View from Above. 125 Years of Aerial Photography*, Martin R (ed.) The Photographers' Gallery: London.

DSM. 2008. *Dyneema®, the World's Strongest Fibre™*. www.dsm.com/en_US/html/hpf/home_dyneema.htm (date of access: 22/01;1;/2008).

Ebert JI, Dubois J-M, Pinsonneault M, Marozas BA, Walker JA, Lind A, Parry JT, Wandsnider L, Camilli E. 1997. Archaeology and Cultural Resource Management. In *Manual of Photographic Interpretation*, Philipson WR (ed). American Society for Photogrammetry and Remote Sensing: Bethesda; 555–589.

Eisenhauer S. 1995. And for my fly rod & reel. *The Aerial Eye* **1**: 6–7.

Eisenhauer S. 1996. Camera cradles revisited. *The Aerial Eye* **2**: 3–4.

Eisenhauer S. 1998. The aluminium cradle. *The Aerial Eye* **4**: 11–12 and 21.

Fosset RC. 1994. *Aerial Photography by Kite*. The Drachen Foundation: Seattle.

Gentles J. 2007. *Kite Aerial Photography. Picavet Test*. www.gentles.info/KAP/PICAVET/experiment.htm (date of access: 05 November 2007).

Gentles Limited. 2007. *Gentled IR*. www.gentles.ltd.uk/gentled/index.htm (date of access: 18/01/2008).

Grog LLC. 2007. *Animated Knots by Grog. Tie Knots the Fun and Easy Way*. www.animatedknots.com (date of access: 23 March 2008).

Hanson CS. 2001. *View from a Kite. Kite Aerial Photography*. Dorrance Publishing: Pittsburgh.

Harding B. 1989. Model aircraft as survey platforms. *The Photogrammetric Record* **13**: 237–240.

Heafitz A. 1992. Excavations at Halai, 1990–1991: Appendix 3: balloon photography. *Hesperia* **61**: 287–289.

Hi Cam. 2005. *Pro X2 Systems*. www.hicam.com.au/pro_x2.htm (date of access: 03 December 2006).

Horton M. 1994. A bird's eye view. *Egyptian Archaeology* **5**: 12.

Jameson MH. 1976. The excavation of a drowned Greek temple. In *Avenues to Antiquity*, Fagan BM (ed). W.H. Freeman and Company: San Francisco; 289–298.

Karras GE, Mavrommati D, Madani , Mavrelis G, Lymperopoulos E, Kambourakis A, Gesafidis S. 1999. Digital orthophotography in archaeology with low-altitude non-metric images. In *ISPRS Vol XXII Part 5W11, Workshop Photogrammetric Measurement, Object Modelling and Documentation in Architecture and Industry, Thessaloniki*; 8–11.

Leffler B. 1999. Knots for kapers. *The Aerial Eye* **5**(1): 8–9.

Loenders J. 2006. *Module voor luchtfotografie*. Unpublished dissertation, Katholieke Hogeschool Sint-Lieven: Gent.

Marks AR. 1989. Aerial Photography from a Tethered Helium Filled Balloon. *The Photogrammetric Record* **13**(74): 257–261.

Messer Group gmbh. Undated. *Helium – The Special Element*. www.messergroup.cn/en/Products_Solutions/Fachbroschueren/pdf/Helium_the_special_element.pdf (date of access: 10 March 2008).

Myers JW, Myers EE. 1980. The art of flying: balloon archaeology. *Archaeology* **33**(6): 33–40.

Myers JW, Myers EE. 1985. [Making] an aerial Atlas of Crete. *Archaeology* **38**: 18–25.

Newhall B. 1969. *Airborne Camera. The World from the Air and Outer Space*. Hastings House: New York.

Owen B. 2006. *An Archaeologist Uses Kite Aerial Photography*. Bruceowen.com/kap/kap.htm (date of access: 17 May 2007).

Owen G. 1993. Looking down on Amarna. *Aargnews* **6**: 33–37.

Picavet PL. 1912. Suspension pendulaire elliptique. *La Revue du cerf-volant*.

Richards D. 2005. *Knot Break Strength vs. Rope Break Strength*. www.caves.org/section/vertical/nh/50/knotrope.html (date of access: 26 February 2008).

Schenken D. 1997. Stereo kiteflying. *The Aerial Eye* **3**: 4–5 and 26.

Schlitz M. 2004. A review of low-level aerial archaeology and its application in Australia. *Australian Archaeology* **59**: 51–58.

Shaw R, Corns A. 2008. Recording archaeological excavation using terrestrial laser scanning and low cost balloon based photogrammetry. In *Proceedings of CAA 2008. Computer Applications and Quantitative Methods in Archaeology, Budapest, Hungary*.

Silberberg MS. 2006. *Chemistry. The Molecular Nature of Matter and Change*. Mcgraw - Hill: Boston.

Shimano®. Undated. *Tiagra*^{TM}. Irvine.

Skarlatos D, Theodoridou S, Glabenas D. 2004. Archaeological Surveys in Greece Using Radio-Controlled Helicopter. In *Proceedings of the FIG Working Week 2004, International Athenaeum Athens, Athens*.

Summers GD. 1993. Photography with a Tethered Blimp. *Aargnews* **7**: 12–17.

Tielkens E. 2003. *L'oeil du cerf-volant. Evaluation et suivi des états de surface par photographie aérienne sous cerf-volant*. Margraf Verlag: Weikersheim.

Verhoeven G. 2007. Becoming a NIR-sensitive aerial archaeologist. In *Remote Sensing for Agriculture, Ecosystems, and Hydrology IX,* Florence, 17–19 September 2007, Neale C, Owe M, D'Urso G. (eds). SPIE: Bellingham; 333–345.

Verhoeven G. 2008a. Exploring the edges of the unseen: an attempt to digital aerial uv photography. In *Remote Sensing for Archaeology and Cultural Heritage Management. Proceedings of the 1st International EARSel Workshop, CNR, Rome, September 30 – October 4, 2008*, Lasaponara, R, Masini, N. (eds). Aracne: Rome; 79–83.

Verhoeven G. 2008b. Imaging the invisible using modified digital still cameras for straightforward and low-cost archaeological near-infrared photography. *Journal of Archaeological Science* **35**: 3087–3100.

Verhoeven G, Loenders J. 2006. Looking through black-tinted glasses – a remotely controlled infrared eye in the sky. In *From Space to Place. 2nd International Conference on Remote Sensing in Archaeology. Proceedings of the 2nd International Workshop, CNR, Rome,* Campana S, Forte M. (eds). Archaeopress: Oxford; 73–79.

Verhoeven G, Smet P, Poelman D, Vermeulen F. 2009. Spectral characterisation of a digital camera's NIR-modification to enhance archaeological revelation. *IEEE Transactions on Geoscience and Remote Sensing* (in press).

Walker JW, De Vore SL. 1995. *Low Altitude Large Scale Reconnaissance: A Method of Obtaining High Resolution Vertical Photographs for Small Areas*. Rocky Mountain Regional Office, National Park Service: Denver.

Whittlesey JH. 1968. Balloon over Halieis. *Archaeology* **21**: 66–67.

Whittlesey JH. 1970. Tethered balloon for archaeological photos. *Photogrammetric Engineering* **36**: 181–186.

Whittlesey JH. 1974. Whittlesey Foundation field activities, 1974. *Journal of Field Archaeology* **1**(3/4): 315–322.

Wolf EB. 2006. *Low-Cost Large-Scale Aerial Photography and the Upland South Folk Cemetery*. Northwest Missouri State University: Maryville.

Zumdahl SS. 1997. *Chemistry*. Houghton Mifflin: Boston.

Żurawski B. 1993. Low altitude aerial photography in archaeological fieldwork: the case of Nubia. *Archaeologia Polona* **31**: 243–256.

DOI: 10.1002/arp