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Are We There Yet? A Review and Assessment of Archaeological Passive Airborne Optical Imaging Approaches in the Light of Landscape Archaeology

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Abstract: Archaeologists often rely on passive airborne optical remote sensing to deliver some of the core data for (European) landscape archaeology projects. Despite the many technological and theoretical evolutions that have characterised this field of archaeology, the dominant aerial photographic surveys, but also less common approaches to archaeological airborne reconnaissance, still suffer from many inherent biases imposed by sub-par sampling strategies, cost, instrument availability and post-processing issues. This paper starts with the concept of landscape (archaeology) and uses it to frame archaeological airborne remote sensing. After introducing the need for bias reduction when sampling an already distorted archaeological population and expanding on the 'theory-neutral' claim of aerial survey, the paper presents eight key characteristics that all have the potential to increase or decrease the subjectivity and bias when collecting airborne optical imagery with passive sensors. Within this setting, the paper then offers some technological-methodological reflection on the various passive airborne optical imaging solutions that landscape archaeology has come to rely upon in the past decades. In doing so, it calls into question the effectiveness and suitability of these highly subjective approaches for landscape archaeology. Finally, the paper proposes a new, more objective approach to aerial optical image acquisition with passive sensors. In the discussion, the text argues that the suggested exhaustive (or total) airborne sampling of the preserved archaeological record might transcend particular theoretical paradigms, while the data generated could span various interpretational perspectives and oppositional analytical approaches in landscape archaeology.

Keywords: aerial archaeology; aerial photography; aerial reconnaissance; airborne imaging spectroscopy; archaeological record; archaeological theory; bias; landscape archaeology; multispectral imaging; survey bias

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1. Setting the Scene

Archaeology becomes more specialised by the day as it continuously integrates new subjects and methods. To properly combine and integrate these methods, reflection is needed. This reflectivity means to assess data acquisition and the grounds on which archaeological interpretations rest [1]. Although some have criticised the general lack of theoretical reflexivity in remote sensing archaeology [2], this specific discipline has seen reflection by archaeologists working in the field. They tried to critically assess how the interpretation of remotely-sensed data can shape the understanding of past cultural and physical landscapes, identify pitfalls in current and future practice and question why things are done the way they are done (e.g., [3–9]). Most papers that tackled the use of remote sensing products in the wider framework of landscape archaeology have thus approached the subject from a more interpretational angle rather than a purely methodological-technological one.

This paper tries to fill this gap. It results from the author's more general concern with the effectiveness of archaeological airborne reconnaissance (see also [10–12]). It reflects on how a more systematic approach to passive airborne optical imaging could yield data that can be used by practitioners of different archaeological theoretical viewpoints. The intention of this paper is to reflect on—and encourage a critical approach to—passive airborne optical imaging for the benefit of landscape archaeology. The text is, however, not a simplistic manifesto to blindly enforce passive optical airborne imaging. Remote sensing data can never be a mandatory or sole source to investigating the landscape. Landscape archaeology must be holistic or 'total' by building up a complementary body of data from multiple distinct survey approaches [13–15] which, when properly integrated, constitute a digital landscape [16] to explore. Obviously, some specific techniques such as pollen analyses or toponymy may have greater importance than repeated airborne surveys depending on the character of the area, the time and money available for the project and the questions being asked [17,18]. These fitness-for-purpose issues are, however, not a part of this article's core scope. The text simply assumes that if a given archaeological landscape project uses remotely sensed optical imagery, they are considered a valid data source to help answer some of the project-specific questions, despite some uncontrollable environmental and climatological biases that might characterise these data. Nevertheless, this assumption does not mean that the subjectivity, which characterises many of the controllable parameters of current passive airborne optical image acquisitions, should not be critiqued. Moreover, the author explains in the conclusion that much of the discussion about the appropriateness of existing airborne imaging methodologies is skewed exactly because of the failure to properly address and resolve the survey methodology issues that this paper tackles.

Overall, the author asks if an 'optimisation' of the dominant airborne sampling paradigms can remove many of the current inherent, but controllable, biases and as such, render the airborne data acquisition phase less subjective, and, in turn, yield a more consistent record to study our past? Thus, the article begins with an introduction to the often ambiguous concepts of landscape and landscape archaeology, followed by a short overview of archaeological remote sensing. Both sections will introduce some key concepts that are vital to evaluate the remaining parts of the paper. Starting from a discussion of the archaeological record and the obligatory samples that are acquired from it, the paper then reviews all the main passive airborne optical imaging approaches that have been used in the past decade. It identifies their strengths and weaknesses regarding eight particular key concepts to highlight their inherent sampling shortcomings and major biases. Following this, the case is made for a more objective approach to aerial optical image acquisition with passive sensors, using a geographical total coverage approach and consistent imaging in particular narrow spectral bands, combined with a large degree of computer-based automation in post-processing. Although the perspective is rather technical-methodological, landscape archaeology frames this review. Also, the article considers and comments on some of the different theoretical contexts surrounding these remote observations.

1.1. The Vogue but Vague Concepts of Landscape (Archaeology)

Depending upon research context, the definition and interpretation of the term 'landscape' changes [19–22]. This disparity in definitions of, and views on, landscape makes it sometimes very difficult to communicate clearly, certainly when the debate is focused on the archaeological study of landscapes. However, even among archaeologists, there is no consensus on the notion of landscape, simply because it remains very challenging to theoretically define concepts of space and place [23]. During the past decades, landscape has become an overused, integrated term, encapsulating a certain amount of human as well as environmental aspects of a delimited area of land. This means that landscape not only includes the combined effects of fauna and flora, geology, topography, soils, waterways and climate, but it also incorporates the cumulative cultural imprints created by settlement building, ploughing, herding, polluting and travelling [24]. This amalgam of environmental and anthropogenic processes has constantly changed in proportion and intensity across space and through time, both very often at vastly different scales. As such, landscapes can be summarised as complex, vague, messy entities that are uninterruptedly shaped through human engagement with them [25,26]; they only possess defined spatial and temporal limits when imposed by analytical procedures and intellectual traditions [27].

Notwithstanding their complexity and vagueness, 'understanding landscapes' is the central aim of landscape archaeology. This archaeological sub-discipline emerged in the mid-1970s [28] and is here roughly defined as the study of all environmental and sociocultural variables influencing the mutual interaction (both physical and perceptual) of humans with their natural environment [29,30]. This means that landscape archaeology is "about what lies beyond the site, or the edge of the excavation" [31] (p. 3), landscape being the physical reality comprising all anthropogenic features and their natural context that exist across space, collectively called 'the land'. In other words, the cultural spaces or rather diffuse human traces such as roads, land division systems or isolated artefacts in between hot spots of activity (traditional 'sites') [32]. This perspective was framed in what became known as distributional archaeology [33], non-site archaeology [34], siteless archaeology [35,36] or off-site archaeology [37].

This process of filling the gaps between the sites gradually became the practical implementation of landscape archaeology since the 1980s, providing valuable information about human exploitation of the environment. However, it also reminded archaeologists of all the possible, subtle or obvious, recursive and mutual interactions of human presence with the land through space and time as well as the strict non-physical aspect of landscape. One that im- or explicitly relates to the various layers of cultural meaning and human value [24,38,39]. Therefore, landscape archaeology is undoubtedly also about how these physical realities are perceived, culturally and socially exploited, understood and given meaning (i.e., 'land-scaped') by past and current human presence [31,40–42]. Landscapes are accepted as being polysemous: geometric, quantitative and economic, but also qualitative, subjectively perceived and socially constructed [43,44]. In other words: landscapes structure and are structured by us; landscapes move, and they move us too [26]. Finally, being the multi-temporal present product of superpositioned and intermingled temporalities, landscapes should not be metaphorically described as palimpsests. In a palimpsest, everything gets erased, but not necessarily so in a landscape. This gives landscapes their cluttered, complex and messy character [45] in which function and meaning are not separable [40].

Bringing the diverse intellectual trends in archaeological theory together with the fact that one can describe landscape only contentiously and ambiguously, has led to several incarnations of landscape archaeology. In other words, a broad array of practices, theories, and tools have emerged to produce knowledge about the physicality and meaning of landscapes in the past [46–49]. Despite this variety of approaches, much European archaeological landscape research has relied on (and still relies on) remote sensing data (although the incorporation of remote sensing methods in landscape archaeology is very variable when considered globally). This relationship should not come as a surprise. Even though they are characterised by diffuse physical and cultural boundaries, a landscape implies a meaningful place for everyday human living. Although the boundaries of these inhabiting and experiencing areas have changed through time, landscape can be considered a concept with an intermediate spatial extent, representing a human scale of lived experience for most of history [24,50]. Being larger than a complex of sites, a landscape has the ideal spatial extent to be observed from above.

1.2. Archaeological Remote Sensing

Archaeology was one of the first disciplines to use remote sensing in scientific investigations [51]. As soon as it became apparent that excavations alone did not provide sufficient clues for understanding the various aspects of past settlements and their transformation over time, 'auxiliary' approaches such as geophysical survey, surface artefact collection and airborne reconnaissance were brought in [52,53]. Although these approaches initially focused on finding 'sites' for excavation, they were instrumental in the development of landscape archaeology (see also Section 3). Today, there is a large consensus among archaeologists that remote sensing encompasses a range of useful observational techniques for discovering and registering archaeological traces and landscape patterning. Although some, mainly British and phenomenological critiques have been formulated on the airborne perspective (see [54] for an overview), remote sensing has not attracted the global and strongly outspoken theoretical controversy characteristic for related tools such as GIS [55]. Overall, non-destructively observing from above is commonly considered a valid backdrop for contemporary European archaeological landscape research [17,47,52,56–61], certainly when fully integrated with other specialised techniques such as artefact survey, geophysical and geochemical prospection, cartographic research, botany and geology. Subsequent sections will comment on the extent to which this background is theory-laden.

Although remote sensing products have already played a fundamental role in formulating explanations of past landscapes, it is still important to review their key concepts and sub-methods. In archaeology, remote sensing is a general name given to all techniques that use propagated signals to observe the Earth's surface from above. This definition rules out terrestrial geophysical methods, even though some scholars call them ground-based remote sensing [62,63]. Their widely differing characteristics allow for the classification of remote sensing techniques in diverse ways: imaging versus non-imaging, passive versus active, optical versus non-optical, and airborne versus spaceborne. Whereas passive remote sensing systems capture naturally occurring radiation such as emitted thermal energy or reflected solar radiation, active systems produce their own radiation. Airborne systems operate from within the Earth's atmosphere, whereas spaceborne systems deploy a sensor mounted onboard a spacecraft (often a satellite) that orbits the Earth. When dealing with an imaging system, the output is an image, whereas non-imaging systems can deliver sounding data or emission spectra.

Archaeological remote sensing relies mainly on the active sounding technique known as Airborne Laser Scanning (ALS) and passive air- and spaceborne imaging in the optical spectrum. However, the selection of appropriate techniques is entirely due to the nature of most (hidden) archaeological remains. Since ALS systems can record sub-canopy features, the vegetation can be digitally removed to expose the underlying terrain and model solid standing structures. Given its capability to digitise surfaces with decimetre- to centimetre-level accuracy, ALS is also able to document the geometry of small topographic undulations such as earthworks or other, even submerged features of archaeological interest [64–68]. Currently, ALS is still considered inadequate to record entirely buried archaeological residues. Since the latter can change the chemical and physical properties of the local soil matrix, they might be disclosed by growing- or ripening-induced differences in the colour or height of vegetation on top of the remains (i.e., crop or vegetation marks, exploited most by aerial survey) or distinct tonal differences in the ploughed soil (soil marks). Although advances in the radiometric correction of ALS data [69] already demonstrated their value to map reflectance differences in soils and plants [70], the amount of spatial detail in these ALS-based images can still not compete with the spatial resolution of data products from the best airborne passive imaging systems. Moreover, reflectance values are only recorded for the wavelength(s) actively emitted by the ALS system. Dedicated air- or spaceborne optical imaging devices can, therefore, more comprehensively map plough-levelled sites through the proxies of vegetation, shadow and soil marks [71].

Although optical electromagnetic radiation conventionally incorporates the ultraviolet to infrared spectrum with wavelengths between 10 nm (0.01 μm) and 1 mm (1000 μm) [72,73], remote passive imaging in the optical regime usually starts at the visible waveband (i.e., 400 nm) [74]. Together with the Near-InfraRed (NIR; 700 nm to 1100 nm) and Short Wavelength InfraRed (SWIR; 1.1 μm to 3 μm), this waveband is known as the solar-reflective spectral range because the imagery is predominantly generated by reflected solar energy (Figure 1). The neighbouring Mid Wavelength InfraRed (MWIR; 3 μm to 6 μm) range is considered an optical transition zone, as the solar-reflective behaviour slowly shifts in favour of self-emitted thermal radiation. In both the Long Wavelength InfraRed (LWIR; 6 μm to 15 μm) and Far/extreme-InfraRed (FIR; 15 μm to 1 mm), the imaging process is almost uniquely governed by the thermal electromagnetic radiation emitted by the scene objects themselves. As a result, the MWIR to FIR optical region is commonly denoted the thermal region.

When the imager uses different spectral bands or channels to capture the reflected or thermal energy, the terms 'multi-' or 'hyper-' spectral apply.

<table>
<tr><th colspan="7">Optical electromagnetic radiation</th></tr>
<tr><th>Division</th><th>Subdivision</th><th>Abbreviation</th><th>Cut-on (nm)</th><th>Cut-off (nm)</th><th colspan="2">Division by imaging principle</th></tr>
<tr><td rowspan="4">UltraViolet (UV)</td><td>Vacuum UV</td><td>VUV / UV-D*</td><td>10</td><td>200</td><td rowspan="4" colspan="2"></td></tr>
<tr><td>Far UV</td><td>FUV / UV-C*</td><td>200</td><td>280</td></tr>
<tr><td>Middle-UV</td><td>MUV / UV-B</td><td>280</td><td>315</td></tr>
<tr><td>Near-UV</td><td>NUV / UV-A</td><td>315</td><td>400</td></tr>
<tr><td rowspan="3">Visible (Vis)</td><td>Blue</td><td>B</td><td>400</td><td>500</td><td rowspan="5">Solar-reflective spectral region</td><td rowspan="5"></td></tr>
<tr><td>Green</td><td>G</td><td>500</td><td>600</td></tr>
<tr><td>Red</td><td>R</td><td>600</td><td>700</td></tr>
<tr><td rowspan="5">InfraRed (IR)</td><td>Near-IR</td><td>NIR</td><td>700</td><td>1 100</td></tr>
<tr><td>Short Wavelength IR</td><td>SWIR</td><td>1 100</td><td>3 000</td></tr>
<tr><td>Mid Wavelength IR</td><td>MWIR</td><td>3 000</td><td>6 000</td><td>Transition zone</td><td rowspan="3">Thermal region</td></tr>
<tr><td>Long Wavelength IR</td><td>LWIR</td><td>6 000</td><td>15 000</td><td rowspan="2">Self-emitted thermal radiation region</td></tr>
<tr><td>Far/Extreme-IR</td><td>FIR</td><td>15 000</td><td>1 000 000</td></tr>
</table>

Figure 1. The divisions of the optical electromagnetic spectrum (* VUV does not perfectly correspond to UV-D. While VUV runs from 10 nm to 200 nm and FUV from 200 nm to 280 nm, UV-D encompasses the 10 nm to 100 nm region and UV-C the 100 nm to 280 nm zone).

Archaeology relies often on multi-spectral satellite sensors to record archaeologically-induced reflectance differences in soil and vegetation [75–79]. It is the combination of an ever increasing spatial and spectral resolving power combined with the frequency by which they can cover large areas of interest and their inherent synoptic perspective (i.e., footage with an extensive spatial coverage) that provide many interesting opportunities for landscape archaeologists when compared to conventional aerial imagery. Besides, satellite sensors can image areas that have limited or no access due to airspace restrictions, bureaucratic red tape or other obstacles to reconnaissance. However, the comparatively limited spatial resolution of spaceborne imagery limits its utility for the discovery and detailed recording of smaller landscape features. When one needs to spatially resolve the soil and vegetation marks that result from small features (such as pits and postholes), an airborne vantage point remains still superior. As a result, satellite reconnaissance is better suited for mapping large-scale and broad landscape features such as paleochannels or detecting upstanding monuments in semi-arid environments, while airborne imaging remains the preferred approach for a detailed study of past geo-cultural activity. Hence, this paper will target only passive airborne optical imaging approaches when presenting methodological reflections and deconstruct existing practices. Moreover, the text implicitly assumes manned platforms.

1.3. Sampling the Archaeological Record

The discipline of archaeology relies by default and as a whole on very limited data, which are from an analytical viewpoint called samples in statistics [80]. In the words of Clarke: "Archaeology in essence then is the discipline with the theory and practice for the recovery of unobservable hominid behaviour patterns from indirect traces in bad samples." [81] (p. 17). With bad samples, Clarke indicates that archaeology does not just simply rely on a sample of the complete, untouched record of all tangible and intangible geo-cultural traces that ever occurred (called the population in statistics and here denoted the potential or target archaeological record). Rather, archaeology and the explanations it tries to construct, rely on a heavily sampled version of an already inherently sampled and thus imperfectly preserved archaeological record, which by itself is only a partial representation of the initial archaeological record (Figure 2).

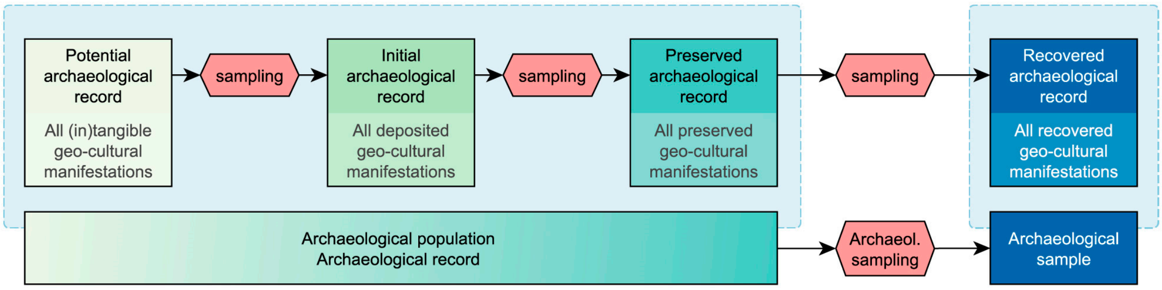

Figure 2. Explanations about the past are based on the deficient and biased archaeological data at our disposal. These data, the archaeological sample (or recovered archaeological record), are only a small subset of all present remains of past human behaviour.

In landscape archaeology, scholars research the continuous record of traces created by human and environmental activity (and their mutual interrelation) that the many post-depositional agencies in that environment (including anthropogenic disturbance) have allowed to be preserved through time. Landscapes are the framework that contain all these testimonies and patterns of human behaviour. The latter, here collectively called the preserved archaeological record, is never pristine. It constitutes only a very limited subset of all those accumulative geo-cultural manifestations and engagements that were included in the initial archaeological record, the latter being only a sample of all possible tangible and intangible human responses to cultural, demographic, environmental and social opportunities that were originally present at a certain moment in time. Depending on the view of the archaeologist, potential, initial and preserved archaeological record can be denoted the 'archaeological record' or the statistical population about which archaeologists want to draw conclusions. Cowgill, for instance, distinguished between a so-called 'physical consequences' population (the initial archaeological record) and a 'physical finds' population (a combination of the preserved and recovered archaeological record) [82]. Both the initial and preserved archaeological populations are thus residual consequences of countless spatio-temporally varying and interacting cultural and natural processes that all act as agents of sampling bias [82–84].

In the fields of metrology and engineering, bias is due to a systematic error and as such an estimate for the closeness of agreement with the unknown 'true' value [85]. Statistically speaking, bias results from an unfair or faulty sampling and is a measure of accuracy. More generally, the concept of bias often denotes the partiality or one-sidedness or unfairness of (one or more) observations, which thus renders that observation also inaccurate according to a third party. Regardless of field, highly accurate observations thus always have a small bias. In archaeology, biased data are characterised by ambiguity, unfair tendencies (systematic over or under representation) and partiality (i.e., inappropriate recovery rate). That is why the preserved archaeological record is by default a progressively biased, distorted and lacking remnant of a once functioning but unknown whole [86].

However, if the past is accessible at all, it can only be understood as a secondary construct that has to be established on the basis of this biased preserved archaeological continuous record. To access this continuum, archaeologist still must rely on finite archaeological samples to infer information about this biased population since observing the totality of a particular aspect of the preserved archaeological record is usually practically impossible or utterly expensive. Lack of consistency and errors in these archaeological sampling processes just add additional bias. It is the latter that archaeologists want to minimise, because the inadequacies in the preserved archaeological record can only be dealt with conceptually.

Since the rise of the processual paradigm, the complex and controversial topic of sampling has received increasing attention in archaeology [87–89]. Although archaeologists always sample according to both theoretical and methodological biases [90], it is generally agreed upon that large samples offer improved accuracy over small samples [91]. It is, therefore, sensible to revise any sampling strategy that knowingly and unnecessarily limits the recovered archaeological record. Only then can these unfortunate and needless constraints on the collected data be mitigated.

The consistent nature of observing is one of the main underpinnings to increase the relevance and accuracy of archaeological data gathering. In other words, only systematic recording in various dimensions can eliminate measurement bias to a large extent and render the archaeological data analytically and interpretationally useful [91,92]. However, lack of consistency is exactly what characterises the most common archaeological optical remote imaging approaches. This is the main rationale that drives this paper and its methodological-technical reflection on (and revision of) current airborne optical sampling approaches.

Finally, it remains important to stress once more the point made at the very beginning of this text. Although this paper acknowledges that topography, soil and vegetation type, land use and climate largely govern (and thus bias) the data generated by passive aerial optical imaging, the article does not provide an in-depth reflection upon these uncontrollable variables since they are inherent to the working principles of airborne passive imaging approaches. In contrast, the text pulls the variables that one can control during the image acquisition into sharp focus. This approach will also make it possible (in Section 8) to juxtapose airborne imaging with excavations and geophysical surveys and criticise some of the general reservations about the fitness-for-purpose of passive aerial optical imaging for the benefit of landscape archaeology.

1.4. Which Theory to Follow?

Reflecting on data acquisition in archaeology necessitates the contextualising of this archaeological practice. In addition, the latter requires some archaeological theory. However, this is a difficult balance and one must take care "to avoid overt theorising which loses touch with the empirical basis; to avoid swinging back too far from theoretical debate into the empirical, and starting bean-counting again" [1] (p. 65). Over the past century, but mainly during the past six decades, successive movements in archaeological theory have influenced archaeological research practices [93]. All of these differing theoretical reflections, of which most seem to originate in other disciplines, stem from the doubts archaeologists have regarding their ability to yield valid inferences about past societies. However, all possible theoretical and methodological stances and their reciprocal relationships have undergone significant changes and multiple critiques to the extent that archaeology still possesses little agreement on theoretical core concepts [94–96]. Or, as Pearce states: theory has become bricolage [97].

When going back to the above-mentioned practical level of landscape archaeology as the study of the geo-cultural spaces between (and incorporating) the sites, remote sensing is in many research contexts a valid means to accomplish this. However, remote sensing data (and the tools to interact with them) stem from the worlds of quantification and generalisation, to which the qualitative and subjective aspects of humanity defended by the broadly labelled post-processual movement, represents a partial reaction [23]. Post-processual archaeologists mainly critiqued the scientific, analytical approach to reach objective conclusions. In that light, it is unsurprising that remote sensing was generally of little interest to them. However, it is not because certain schools of thought will more readily adopt airborne optical imaging that opposing theoretical schools cannot rely on airborne observations and learn from them. Post-processualism, for instance, questioned the relationships between the observed and the object of study. From this point of view, aerial imaging has quite some notions to contribute. It also indicates that most theories relate to the interpretive framework of (landscape) archaeology. They are concerned by how information (and in a later stadium knowledge) are gained from archaeological data and why certain data are gathered. They widely disagree on the extent to which archaeological data are theory-laden, but debate only to a lesser degree the data collection procedures themselves. In contrast to what some might believe, deciding upon a specific method does not necessarily assume a particular theoretical orientation. Many archaeologists even (implicitly) believe that remote sensing is independent of any theoretical foundations, that it is 'theory-neutral' when it comes to landscape archaeology [2,98].

This aura of theoretical neutrality stems from the beginning of the 20th century and the fact that remote sensing methods were often developed outside the main theoretical reflections. However, any aerial image is an archaeological piece of data just like any other source such as a ceramic bowl. Both the photograph and the ceramic bowl are mere samples of the preserved archaeological record (see Section 1.3) and have to be the subject of a particular theory-driven interpretation, the outcome of which is affected by many underlying assumptions and pre-understandings [99]. Although the theoretical interpretational frameworks that enable the reading and narrativising of aerial images are not a part of this paper, it must be clear that the archaeological function of airborne imagery (or any remote sensing output for that matter) are far from being culturally unbiased and theoretically neutral [2,100]. Moreover, also the application of a specific method is governed by theory, since one always consciously chooses airborne remote sensing as (one of) the data collection methods to answer an (often tacit) theory-based research problem. Again, this does not mean that the choice for airborne imaging automatically assumes a particular theoretical orientation, certainly not in a time where theory seems to have become less partisan and more pragmatic.

Any aerial image only depicts a few dimensions of the contemporary, preserved archaeological record, most of it through proxies like soil, shadow and vegetation marks. The values of and relations between the individual pixels must still undergo an evidential interpretational stage (which in itself poses still many problems in archaeology [101]). The very process of passive airborne imaging should, however, be executed as exhaustively and systematically as possible (given the contemporary technological constraints of observing various dimensions). Whether the landscape is considered abstract, quantifiable, static and neutral or rather seen as a humanised, qualitative, dynamic and contextual entity [39], landscape archaeology is always about totality: it is about all kinds of people and the superposition and intermingling of all possible landscapes. This paper will, therefore, explore the need for a more holistic approach to airborne data collection in all feasible dimensions (being spatial, spectral and temporal among others). It proposes several improvements to the current dominant optical aerial imaging approaches so that the airborne data gathering stage can become of undeniable use to many possible theoretical perspectives on landscape.

In this way, the dominant form of archaeological airborne remote sensing can move beyond its traditional cultural-historical point-based approach and provide data that are deeper and more explicitly rooted within the application of landscape archaeology. Moreover, removing much of the existing selectivity from the airborne data collection phase essentially mitigates major sampling biases and largely ignores the social context and pre-understandings of the aerial archaeologist, thereby allowing optical aerial imaging to transcend theoretical perspectives and become less theory-laden. Too often, incorporating (new) digital technologies in archaeology while lacking any theoretical framework is said to be meaningless. Albeit correct to some extent, this paper hopes to show that even the best conceptual framework will not prevent any biased and incompetent use of technology (hard-plus software) and methodology. Fancy theories can still lead to the acquisition of useless data from which insupportable, meaningless and even erroneous conclusions are drawn.

In this light, the next section will present eight particular characteristics that apply to all passive optical airborne imaging approaches. Afterwards, this paper will outline the methodological-technological pros and cons of the main passive airborne optical imaging approaches applied in archaeology. Using these eight features, it can be shown that all airborne imaging techniques are—implicitly or explicitly—sub-par samplers of one or more dimensions of the preserved archaeological record, thereby introducing major bias and subjectivity into the collected data. It is important to mention once more that this assessment does not equal the often implicitly accepted (and during cultural-historical and processual times outspoken) objective and neutral nature of remotely sensed imagery. The choice of a specific study region, aircraft, flying height, pilot, imager, lens and image acquisition time are all very subjective decisions. However, subjectivity should only take its leading role after the data acquisition stage, when experience, intuition and knowledge govern data processing, visualisation, interpretation and information synthesis.

2. Capturing Multi-Dimensionality in Eight Key Characteristics

2.1. Bias Versus Cumulativety

Earlier (Section 1.3), the case was made for a consistent recording of airborne data to eliminate measurement bias as much as possible. This text also argues for an airborne approach that maximally excludes potential data partiality by exhaustive sampling. In other words, the recovery rate of the preserved archaeological record should be as high as possible. When the airborne observation does not adhere to both conditions, it is denoted biased. Not that this concept of archaeological bias strongly deviates from the metrological idea. In its strict mathematical sense, bias cannot be reduced, let alone eliminated, by acquiring more samples. Since it is the difference between the mean of many observations and the true value, a single measurement is also considered unbiased in a strict statistical sense.

However, aerial archaeological survey is a strange animal. Not only should it seek to minimise partiality by an exhaustive sampling scheme (which equals in some aspects a total coverage approach—see Section 3), it should also be executed repeatedly. Although the proponents of the empirical approach would always advocate repeatable aerial data collection sorties as they believe that more data will lead to greater veracity, even those following deductive approaches have to resort to repeated surveys if they want the aerial data collection to be effective. Even with a total approach, the visibility of (predominantly) vegetation marks in a specific part of the electromagnetic spectrum depends on numerous variables: geology, land use, plant species, soil humidity, erosion processes and weather conditions during the flight among numerous others. Since the interactions between the many conditions do often not yield conditions that are ideal for observing crop, shadow and soil mark features with a specific imaging setup, a cumulative approach to partially resolve these uncontrollable biases is imperative [102].

2.2. The Usual Suspects

Spatial, temporal, spectral and radiometric resolving power are the first four characteristics that can express how much a specific airborne data collection strategy is prone to induce bias in the imagery recorded. They stem from the fact that digital imaging sensors always represent averages of the spatial, temporal and spectral dimensions. The macroscopic space we live in is—according to Newtonian physics—four-dimensional. Any 'event' in the universe can be defined by a location (x, y, z) and a time of occurrence (t), making this event a four-dimensional entity [103]. However, in addition to this one temporal and three spatial dimensions of the universe, more or less every variable can *sensu stricto* be thought of as a dimension [104]. Just as time is a variable, the same goes for colour, temperature or the number or pottery sherds per metre squared. For remote sensing data, a sampled spectral and radiometric dimension is usually defined in addition to the temporal and spatial ones. Note that resolving power denotes the characteristic of the imaging system, while the term resolution is used when talking about the image itself.

Spatial resolving power refers to the ability of an instrument to distinguish between neighbouring objects. It is expressed as the reciprocal of spatial resolution [105]. Although the final spatial resolution of an image depends on many factors, one of the key factors is the so-called GSD or Ground Sampling Distance. Most imaging sensors have a sensor that consists of individual photosites (see Figure 3). The distance from the centre of one photosite to the centre of the neighbouring photosite is denoted the detector pitch. The GSD is the corresponding distance projected in object space, stating the horizontally or vertically measured scene distance Δx between two consecutive sample locations. Although the detector pitch is a fixed property of a sensor, it can generate images with different GSDs. Among other factors, the GSD is determined by the scene's local topography, the distance of the camera to the scene and the focal length of the lens. To counteract observational bias towards larger features, smaller GSDs are important.

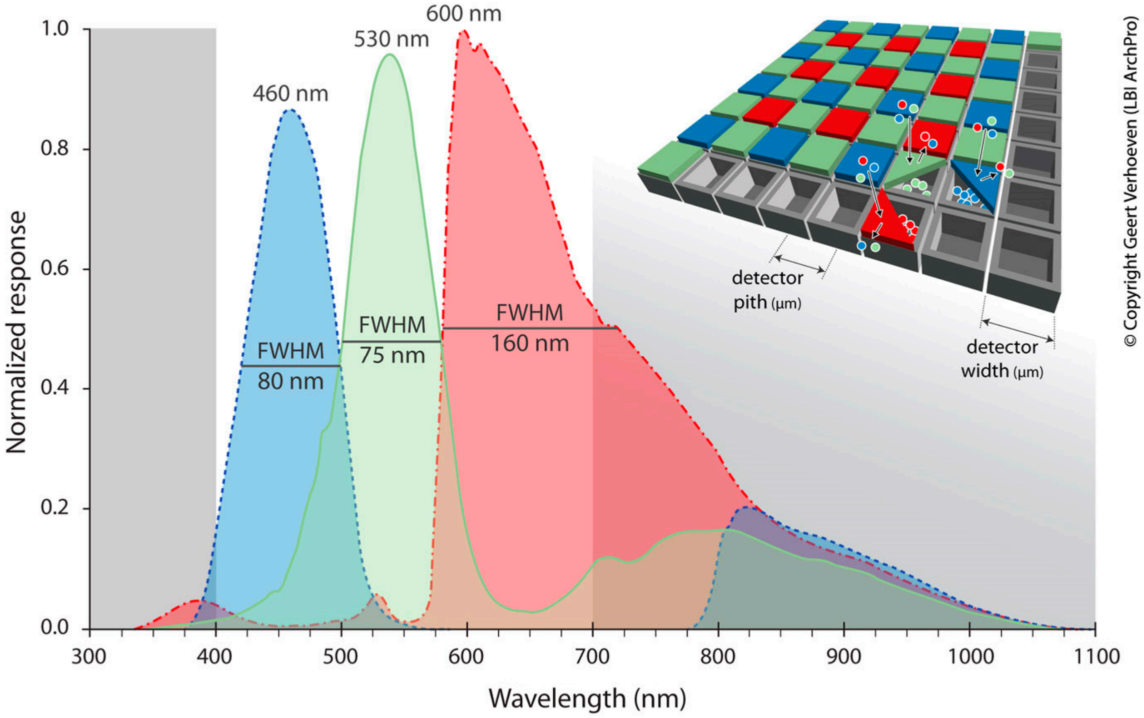

Figure 3. The working principles of a typical digital image sensor inside a photo camera. The relative spectral response curves obtained from a Nikon D200 without internal blocking filter reveal that the Blue, Green and Red channels have a FWHM of 80 nm, 75 nm and 160 nm, respectively. Note that the red channel of an unmodified camera will have a FWHM of about 50 nm since the camera will not be responsive in the invisible near-ultraviolet and near-infrared regions (both indicated in grey). With maxima at 460 nm, 530 nm and 600 nm, all bands are separated by 70 nm.

Sampling the time dimension is related to the imager's integration time or shutter speed during image acquisition. However, the temporal resolving power of an imaging system generally refers to the repeat period or the capability to view the same scene at regular intervals. This characteristic was included here since repeated airborne observations are key to build up a cumulative data record.

The spectral resolving power quantifies the spectral details that can be resolved by the imaging sensor. The Full Width at Half Maximum or FWHM is usually applied as the measure of spectral resolving power. The FWHM of a spectral band quantifies its spectral bandwidth at 50% of its peak responsitivity. Commonly, FWHM is expressed as a wavelength difference range $\Delta\lambda$ and measured in nanometre or micrometre (see Figure 3). To preserve spectral details, the spectral pass band (in terms of FWHM) should have a width smaller or comparable to the spectral details in the signal. Broad spectral bands just integrate over a too wide range. They average subtle spectral details away and create ambiguity. To sufficiently resolve small spectral features, the placement of the spectral bands—expressed as an interval in nm—is as important as the spectral bandwidth. Not being able to record the contrast exhibited by vegetation and soil marks will thus automatically lead to biased data.

Besides these three sampling processes, digitising an analogue signal also encompasses quantising the sample values to a discrete Digital/Data Number (DN). The total possible range of different DNs or quantisation values an imager can create is termed the tonal range. An image´s tonal range is thus fully determined by the bit depth of this quantisation process: quantisation with N bits maps samples onto a discrete set of 2^N values. This quantisation (or radiometric sampling) provides images with a radiometric resolution. The radiometric resolving power of an imaging sensor refers to the capability of that sensor to discriminate two targets based on their emittance or reflectance, a value that is among other factors dependent on the imager's bit depth. Digital images are thus sampled and quantised representations of a scene, defined by a multi-dimensional matrix of numbers [106]. If their spatial, temporal, spectral and radiometric resolution becomes too coarse, they create ambiguity. Since all four characteristics are the result of finite interval sampling processes, a digital image will thus always induce partiality. The smaller the sampling unit becomes (i.e., the more exhaustive the sampling gets), the less biased archaeological image data will be (note again that this does not relate to the unique meaning of bias in measurement theory). Key is to minimise this partiality and ambiguity by optimising all four key characteristics.

2.3. From Availability to Processing Complexity

While an imaging sensor´s resolving power and the resolution of an image are thus quoted in the spatial, spectral, temporal and radiometric measurement dimensions, this paper defines four additional but equally important properties to describe an aerial archaeological imaging solution that are not part of the usual remote sensing suspects: cost, availability, geographical bias and processing complexity.

Cost refers to the financial cost of acquiring the imaging system as well as its operational costs. Availability indicates how easy it is to have the system in operation at a certain place and a certain time. Systems that are very affordable or whose handling is straightforward, are generally easy to come by and will, therefore, be much more available than their expensive, highly specialised counterparts. When an imaging system is not available or operational funds are lacking, no data are collected or at least not when initially planned (e.g., when the conditions are favourable to record vegetation stress). Both factors might prevent the vital cumulative approach to data collection and even induce strong biases by limiting the area and the time frame in which the survey can be carried out.

The main problem with much existing aerial imagery is, however, its strong geographical, observer-related bias. The latter refers to the coverage of the scene during the data acquisition phase: is every part of the study area covered or are only selected views obtained? When airborne imagery exhibits a geographical bias, space becomes anything but neutral and remote sensing data far from a contiguous objective-like background. Since this type of bias is prevalent and of high importance, the next section covers it at length.

Finally, processing complexity encompasses all the geometric and radiometric corrections that should be executed before any of the interpretational processes can start. Highly complex post-processing chains prevent data from being considered as a relevant source in landscape archaeology, as such creating one more type of bias. Of course, one could always epistemologically argue that only archaeological research itself produces lacking data since archaeological data themselves are complete and data gaps only emerge once those samples are considered evidence of something [86]. However, since aerial image-based interpretations are used in landscape archaeology to grasp complex aspects like human behaviour, passive airborne optical imaging approach(es) should from the very start minimise data deficiencies and additional unnecessary biases. This can be obtained by maximising instrument availability and the amount of systematic observations in the various dimensions on the one hand, and minimising their operational costs, geographical bias and processing complexity on the other. The next sections will delve deeper into all individual techniques for archaeological passive airborne optical imaging, being: observer-directed aerial photography, blanket aerial photography, multispectral imaging and airborne imaging spectroscopy. All four will be assessed in the light of these eight key concepts (although less stress will be put on the radiometric and temporal resolving power of the systems given their overall good to excellent performance). A tabulated overview of these accounts can also be found in Table 1. Along the way, some thoughts on equipment- and terminology-related issues will be provided as well.

Table 1. Overview of the main passive imaging solutions in the optical domain and how they score for the eight key characteristics. +, 0 and − indicate good, neutral and bad, respectively. Scoring is specifically for archaeological purposes and established by mutually weighing all solutions.

Method	Spatial	Spectral	Temporal	Radiom.	Cost	Availability	Geo-bias	Processing
Observer-directed aerial photography	+	−	+	+	+	+	−	0
Blanket aerial photography/multi-spectral imaging	+/0	−/0	0	+	0	0	+	+
Airborne imaging spectroscopy	0	+	0	+	−	−	+	−

3. How It All Started: Observer-Directed Aerial Photography

Concerning the first phase of archaeological aerial prospection from manned platforms, much credit must go to Osbert Guy Stanhope Crawford (1886–1957). This Englishman is considered to be the inventor of scientific aerial archaeological reconnaissance, and his work in the 1920s and beyond was the basis for the future development of the discipline that became known as aerial archaeology [107–109]. Thanks to Crawford's leading role, archaeologists recognised the potential and convenience of straightforward aerial observations to unravel and study the past. His positivist perspective made Crawford consider aerial photographs as a neutral representation of objectively existing archaeological sources. Despite the processual archaeology-inspired discussions on various aspects of the method, the currently dominating practice of archaeological aerial photographic reconnaissance has not witnessed major changes since the work of Crawford. In general, aerial photographers engaged in this type of prospection acquire photographs from the cabin of a low-flying (anywhere between 300 m and higher), preferably high-wing aircraft with lift-windows to obtain a wide, unobstructed view of the scene below them. For a maximum working angle, the passenger door might be removed as well. A small- or medium-format photographic/still frame camera is hand-held and equipped with a lens that is commonly uncalibrated [110,111]. Once airborne, the archaeologist flies over targeted areas, trying to detect possible archaeologically-induced landscape features. After an archaeological or environmental feature of interest is detected, it is orbited and photographed from various positions. Although a photographer might create near vertical photographs (or simply 'verticals') during such an archaeological reconnaissance sortie, the vast majority of the photographs will be oblique in nature in that the optical axis of the imager intentionally deviates more than three degrees from the vertical to the earth's surface (Figure 4).

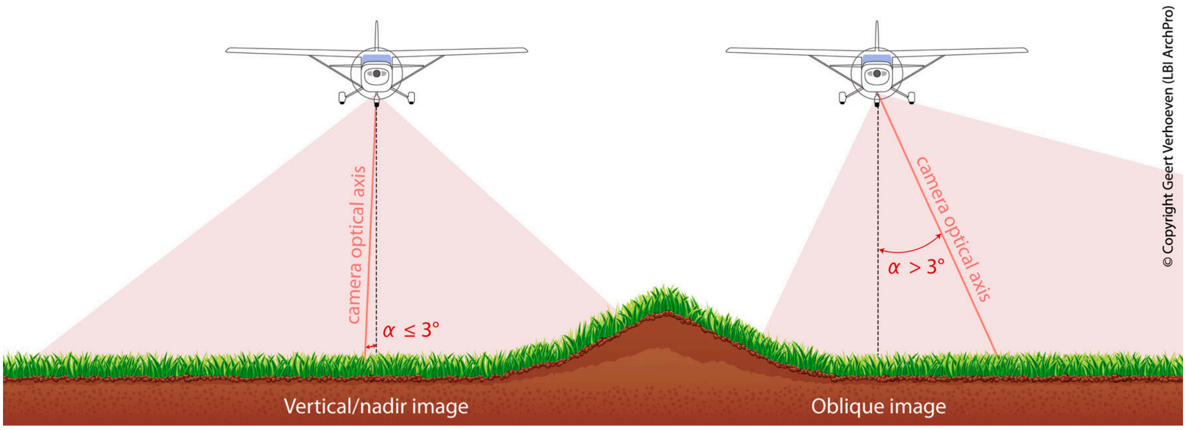

Figure 4. Vertical versus oblique aerial imaging.

Depending on the visibility of the apparent horizon, the image is then further classified as low oblique (i.e., the horizon is not included) or high oblique [112]. Sometimes, the threshold between low and high oblique photographs is also quantified at 30° [113]. Since this type of archaeological aerial prospection primarily generates oblique images (or simply 'obliques') of archaeological interest, archaeologists in Great Britain but also in other parts of Europe have used 'oblique survey' as shorthand for this type of observer-directed or observer-biased survey strategy (the latter terms coined by Palmer [114]). In the mapping and surveying community, this kind of photography is sometimes denoted free-camera oblique photography, being " ... an enjoyable and to some extent creative form of aerial photography ... where the pilot and photographer have the task of photographing random targets on a speculative basis" [115].

Since the 1930s, this free-camera, observer-directed aerial surveying has been the workhorse of all archaeological airborne remote sensing techniques. Its success lies mainly in its straightforward execution as well as the abundant availability and moderate cost of small aeroplanes and photo cameras. The combination of its capacity to repeatedly cover relatively large areas with ample spatial detail (typically a GSD of 5 cm to 10 cm) turns it into one of the most cost-effective methods for site discovery—or at least, that is what it is often told to be e.g., [116,117].

Despite its efficiency in certain areas and periods, the main disadvantage of this reconnaissance approach lies in its observer-directed nature which generates extremely selective, pre-interpreted [6] and thus utterly biased data that are completely dependent on an airborne photographer recognising archaeological phenomena at a relatively high air-to-ground speed. Subsurface soil disturbances that are visually imperceptible at the time of flying, or those that are simply overlooked, will not make it into a photograph. Moreover, the observer might fail to record certain features, even when looked at, because he/she is too tired or they are not part of his/her expectations or repertoire of known sites (see Cowley [18] for a more thorough discussion of this topic). Alternatively, the surveyor might simply ignore existing features and create false patterning by flying where the archaeological 'hot spots' (a.k.a. 'honey-pots') or the 'familiar stuff' can be found [4,118,119]. Aerial archaeological pioneers such as John Kenneth Sinclair St Joseph (1912–1994) are (in)famous for pursuing mainly Roman military archaeology [120,121]. To them, but also too many of their successors, taking aerial photographs is like collecting stamps. In a sense, observer-based archaeological aerial photography is still pursuing the same goals as those of the first decades of the 20th century. This site-based approach contrasts with the inherent complexity of landscapes and their internal relationships landscape archaeology tries to unravel. Also, pre-interpreting the object of study before collecting data about it renders this type of aerial observations entirely subjective.

Airborne imagery acquired during an observer-directed sortie is thus nothing but an arbitrary sample, based on the perception, interest, motivation, knowledge, expectation and logistical capabilities of the person behind a highly unoptimised data recording system called photo camera. When also taking the indispensable need for favourable interactions between all the uncontrollable variables as an additional bias into account [17,122], one can call into question the appropriateness of such haphazardly collected data to make inferences about the landscape as a whole. Yet, these biased data and the knowledge created from this century-old approach to aerial imaging continues to frame much of the research in landscape archaeology.

To counteract any of these obvious geographical biases, several scholars have already questioned this particular reconnaissance strategy over the past two decades. Although flying higher and/or with a shorter focal length can draw more of the landscape into the photograph and a second observer/photographer onboard might certainly increase the archaeological detection rate, several papers also pointed out the advantage of a geographical 'total coverage' or 'seamless' approach [114,123–129]. Moreover, since photographs that result from such a blanket survey are much better suited for automated image processing workflows, they also mitigate the prevalent bias that is created by simply not using these aerial observations.

4. Removing the Camera-Angle Delusion: Total Coverage Aerial Photography

During a total coverage or block survey sortie, photographs will predominantly be acquired with expensive, accurately calibrated, built-in (versus hand-held), gyro-stabilised and low distortion mapping frame cameras (often referred to as metric or cartographic cameras [130]) to make sure that all photographs are nadir/vertical images. These cameras are solidly housed and operated in bigger and higher flying aeroplanes. Images feature a GSD of 25 cm or smaller and are acquired in parallel strips at regular intervals, generally with a substantial frame overlap: in one flight strip, each photograph has a generally accepted degree of overlap of circa 60 ± 5% (figures to 90% can be found as well, see [113]) with the following and preceding image (longitudinal overlap). Adjacent strips have on average an overlap of 25% to 40% (lateral overlap) [115]. The camera is pointing directly down to the earth to acquire (near) nadir photographs. Because a perfect vertical is seldom achieved, an image with an angle of less than or equal to 3° is called vertical [131]. Analogous to the oblique survey approach, archaeologists began to use 'vertical survey' as shorthand for such total area coverage flying strategies. Although one could indeed argue that both flying strategies primarily deliver these types of images, this archaeological habit remains a very inappropriate way of categorising aerial survey approaches.

Just as the observer-directed flying strategy can yield vertical imagery, these aerial block surveys can deliver oblique imagery as well. This has never been more evident than in the past fifteen years, during which the geospatial community re-introduced oblique imagery for measuring applications. Although tilted views had been very popular in the 1920s to 1940s for mapping, surveillance and reconnaissance purposes [132], extracting accurate geometry from aerial images has been limited to blocks of vertical images afterwards. The recent revival of the tilted views—acquired during total coverage mapping surveys—was mainly triggered by Pictometry. Since this New York-based imaging company introduced in 2000 its PentaView capture system consisting of five cameras (of which four were taking oblique images, while the central one was directed nadir [133]), the properties of the acquired oblique imagery have been opening many eyes. As a result, a strong movement towards mapping approaches that integrated oblique images with the more traditional vertical ones was created [134,135]. This trend is now exemplified by the growing number of manufacturers that create digital multi-camera systems in which the vertical mapping camera is complemented by one or more oblique mapping cameras—for example IGI's Penta DigiCAM [136] or Microsoft's UltraCam Osprey family [137] (Figure 5).

Figure 5. The Microsoft/Vexcel UltraCam Osprey Prime II for combined nadir and oblique image capture. Image source: https://ultracam.files.wordpress.com/2014/04/ucop_2.png.

Although the current evolution and use of these systems are mainly driven by the major developments in the fields of computer vision and photogrammetry [138], the resulting imagery is also an excellent source of geo-information for many other fields. The strongest selling point of these obliques is their intuitive nature and rich content: not only do they come close to the standard human perception of objects or scenes while standing on a hill or in a high tower [139,140], they also make it easier to map façades of houses, hence providing a complete description of built-up areas [141,142]. Although parts of vertical structures such as houses, electricity pylons, trees and lamp post might indeed remain occluded in a vertical view, the information that oblique imagery delivers about vertical structures is only of minor importance in most landscape archaeology projects. The reasons for the enthusiastic revival of the slanted viewing geometry in the geospatial industry do thus not hold (or only to a minor extent and in specific cases) for most archaeological landscape projects. Moreover, nadir views provide a more than satisfying alternative to the extremes of oblique imaging for rendering shadow and colour-difference based marks [10].

From the statements above, it should be clear that the traditional archaeological remote sensing dichotomy between oblique and vertical aerial photographic reconnaissance—in which either type too often indicates a specific flying approach—is a highly inappropriate one. This terminology should be left behind in favour of observer-directed versus total coverage or block survey, both capable of generating oblique as well as vertical aerial photographs. Although the terms biased versus unbiased aerial survey are sometimes coined [114,143], their usage is also discouraged since many other biases remain. If used, one could refer to these survey strategies as being geographically unbiased—as was also done by Mills [125]. That is, geographically unbiased at least inside the survey area itself, since the specific choice of the latter is also governed by many personal and practical factors.

5. Increasing the Spectral Dimensions: VNIR Aerial Imaging

Despite many advantages, both geographically biased and unbiased aerial photography are typically characterised by major spectral shortcomings. In archaeological observer-biased aerial photography, the human visual system governs the survey working principles. However, both the human eye and a standard photo camera only create useful data streams using light (i.e., the visible electromagnetic spectrum). Although several archaeologists have at a certain point in their career experimented with false-colour or pure Near-InfraRed (NIR) airborne imaging (consider [144] for an extensive overview) or even imaging in the near-ultraviolet [145,146], the majority of aerial footage has been acquired with photographic media that were sensitised to wavelengths between approximately 400 nm and 700 nm. Although striking and revealing images have been obtained in this way, the detection of vegetation marks (and to a certain extent soil and other marks) becomes impossible in less-than-optimal circumstances. The slight differentials of height and colour in crops might simply exhibit too low contrast with the surrounding matrix to be noticed in the visible spectrum (Figure 6). As a result, the aerial observer will never orbit nor document visually imperceptible soil and crop disturbances.

Since most mapping cameras are multispectral devices that capture imagery in one NIR and three visible channels (encompassing the so-called VNIR spectrum), NIR blanket coverage generated during a block sortie tackles the issue mentioned above. However, both standard photographic solutions as well as multi-spectral imagers capture reflected solar radiation in spectrally broad wavebands. A typical colour photograph records the visible spectrum in three wide Red, Green and Blue channels (with their FWHM approximately 80 nm; Figure 3), while a NIR image generally encompasses a 200 nm waveband. From the perspective of feature recovery-rate, this is a subpar approach since particular diagnostic spectral vegetation features are often only a few nanometres wide. (Note again that this text mainly focuses on vegetation marks due to their abundance and potential to disclose very detailed morphological information about the totally buried archaeological features).

This makes acquisition of data with a high spectral resolution necessary when one seeks to assess small variations in—for example—plant physiology and minimise spectrally-induced ambiguity in the data. Vertical and oblique photography, even when executed beyond the visible waveband, thus significantly reduce the diagnostic accuracy of vegetation investigation. Despite their potentially high spatial resolving power, they spectrally undersample the at-sensor radiation and mask the spectral features that are too narrow to be distinguished [11,147]. Although more dedicated multispectral sensors like the Daedalus 1268 Airborne Thematic Mapper have been developed and used profusely in archaeological research [148–152], those cameras commonly lack the high spatial resolution advocated above. They are also ill-suited for fast deployment in the small two- to four-seat aircraft that are typically used for an archaeological aerial survey. Nevertheless, the resulting images enable the generation of radiometrically corrected orthophotographs and Digital Surface Models (DSMs).

Figure 6. Visible (**A**) and NIR photograph (**B**) of the same area in *Portus*, Italy (41°46′30′′N, 12°15′51′′E—WGS84). Note the many features that are visible in the NIR image but go undetected in the conventional photograph.

6. Overcoming the Spectral Delusion: Airborne Imaging Spectroscopy

To resolve this spectral resolution issue, archaeologists have started to investigate Airborne Imaging Spectroscopy (AIS), also known as Airborne Hyperspectral Scanning (AHS). AIS is a passive remote sensing technique that digitises the earth's upwelling electromagnetic radiation in a multitude of small spectral bands. Compared to most multispectral sensors, hyperspectral sensors have a higher spectral resolving power (typically an FWHM of around 10 nm in the VNIR range) and capture more and (nearly) contiguous (i.e., adjacent and not overlapping) spectra [153]. Although the borderline between multi- and hyperspectral imaging is rather discipline dependent, ten to twelve spectral bands is often taken as the threshold [154]. In other words: tens to hundreds of small bands of electromagnetic radiant energy are captured per pixel location (Figure 7). Through a combination of all spectral data acquired from a particular spatial location, every pixel of the final image holds the spectral signature of the material that was sampled at that specific location.

AIS is typically used to image entire areas without having geographical data gaps. So far, AIS has been used in several archaeological projects, for example [150,155–168]. The success rate regarding archaeological subsurface structure detection is, however, variable and less effective applications seem to be connected with the lower spatial resolutions of the acquired datasets (in most cases the GSD ranges from 1 m to 4 m). Although the current generation of AIS sensors easily enables a GSD below 50 cm when flown low and slow enough, the visible image detail is still not comparable with conventional three-band aerial photographs.

Despite better spectral resolution and improving spatial resolution, working with AIS data necessitates a certain amount of expert knowledge and specialised software. Assuming that the image geometry and georeferencing can be handled correctly—which is far from a trivial task—one needs to deal with the data quality and dimensional overload by denoising procedures and intelligent data mining approaches. Even though specific archaeological tools such as the MATLAB-based ARCTIS toolbox [169] have been developed to answer these needs, the issues mentioned above are still a limiting (i.e., biasing) factor for the widespread application of AIS in archaeology. Finally, the cost of an AIS flight still places it out of reach of most institutions, despite the steadily decreasing prices due to increased demand in non-archaeological communities. If, however, hyperspectral data with a high spatial resolution are used in combination with powerful processing algorithms, AIS does certainly have a clear potential in areas where vegetation marks do not appear clearly in broad-band multi-spectral setups (e.g., [158,168]).

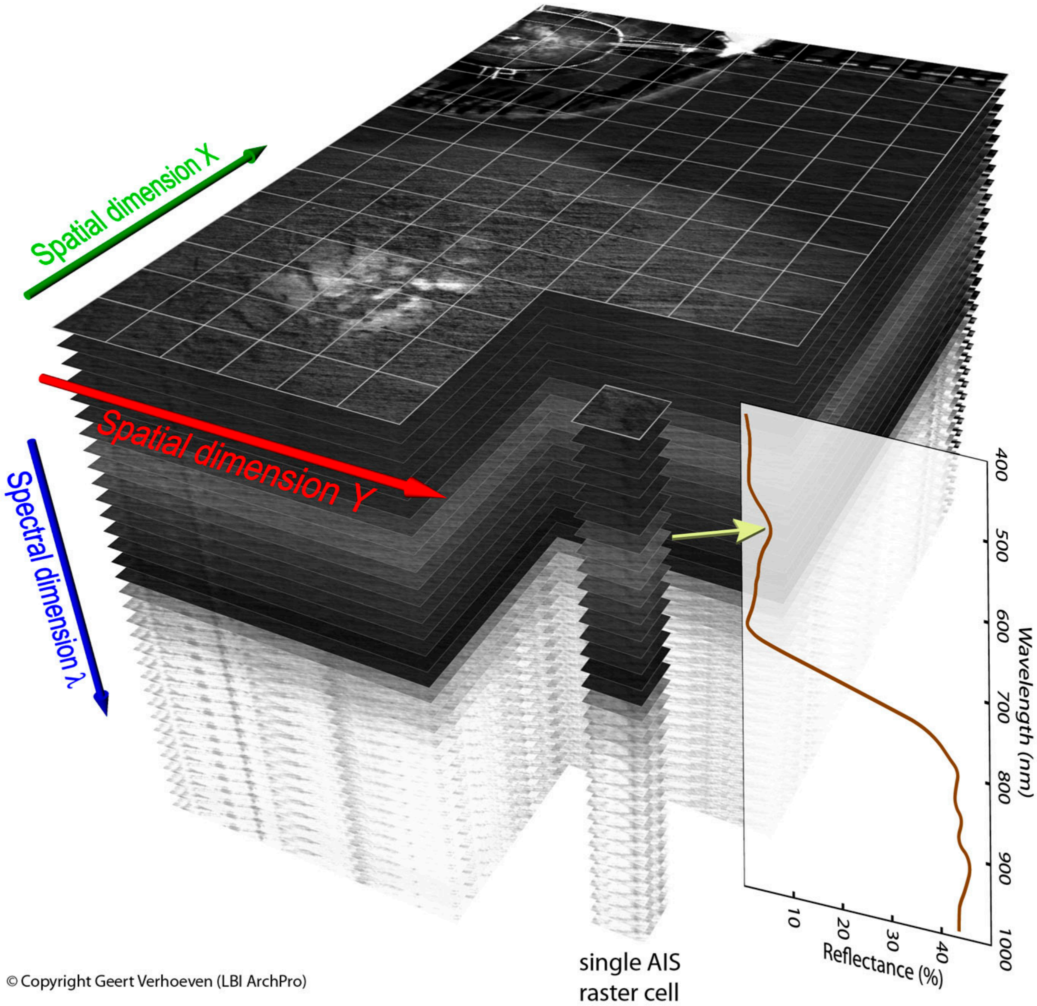

Figure 7. Visualisation of an airborne imaging spectroscopy data cube.

7. Take the Best, Leave the Rest. A Discussion

After this reflexive approach, it thus seems that, despite a hundred years of technological evolutions and methodological developments, many observational shortcomings still hamper passive airborne optical imaging to truly benefit the many flavours of landscape archaeology. This results in a wide variety of biases, both in the data and the subsequent usage of them:

- spaceborne data, consistently acquired over extended areas and often in invisible wavebands, might tackle the observer-directed and visible-radiation-limited biases. However, the data are less (or not at all) suited for the discovery and detailed recording of small archaeological features, as the spatial resolving power of the sensors exceeds one metre in all but a few panchromatic cases (a panchromatic image is a greyscale image created by one spectral band that is sensitive to more or less all ('pan') wavelengths (or colours, hence 'chroma') of visible electromagnetic energy). Moreover, the spectral bands of older spaceborne imagers (i.e., those whose products are freely available) are generally too broad or misplaced spectrally to truly detect the plant stress that governs vegetation marks [170];

- conventional airborne photographic imaging approaches are dominantly observer-directed, creating a strong geographical bias. They also lack the spectral resolving capabilities that are needed to digitise subtle reflectance features;
- existing multispectral solutions are often limited to four broad bands while the instrumentation is expensive and impossible to easily (de)mount into a light aircraft;
- hyperspectral imaging sensors do acquire data in narrow wavebands and are usually flown with a total coverage strategy in mind, but the combination of affordability, availability, data complexity, moderate temporal resolution and generally lower spatial resolving power also significantly restrict its frequent use (even of existing data) in archaeological research. Various biases and a lack of cumulative data are the result;

These remarks are not to diminish the importance of data collection strategies used so far, but the tools and knowledge are now here to eliminate several of these shortcomings. At the turn of the 21st century, Bewley and Rączkowski stated that "in examining future developments it is becoming clear that we must hold on to the best of the old and embrace the best of the new" [171] (p. 4). From the statements above, it seems that a more technologically adept archaeological airborne reconnaissance system would combine the cost-effectiveness (from a hardware point of view), availability and operating flexibility as well as the spatial and temporal resolving power of the observed-directed photographic approach. In addition, it should allow a geographically unbiased total coverage in a selection of narrow visible and invisible spectral wavebands that are suitable for detecting vegetation and soil marks.

In the author's view, the last two characteristics are crucial if the aerial archaeological community wants to evolve to an improved airborne data acquisition that aims at a more consistent record of our past. The next sections outline a proposal to that end. In short, the text further details why a rather dense airborne sampling of various dimensions of the preserved archaeological record could naturally span several perspectives and oppositional analytical approaches that are commonplace in landscape archaeology. As such, this observational (i.e., data gathering) phase might to a large extent transcend major theoretical paradigms. This proposal does not have to stay a purely hypothetical one, as Verhoeven and Sevara [12] have recently shown how this could be materialised and put into practice.

7.1. Geographically Unbiased and Vertical

From a technological point of view, geographical total coverage aerial imaging is not novel at all. However, it becomes innovative in archaeology as soon as it is executed with the same intensity as observer-directed aerial surveys. When total coverage passive aerial optical imaging would be performed by default, the uniformity of the aerial archaeological data sets would benefit enormously. Passive airborne optical image collections would be freed of (most of) their inherent weaknesses such as the observer's experience, a priori knowledge and many other methodological biases [4,18], although Wilson claims them to be unavoidable features of aerial reconnaissance [119].

The acceptance and implementation of such a strategy can, however, only be fruitful if one distances themselves from the common approaches by which block surveys are executed. It still holds true that most archaeological features appear on vertical photographs (acquired during a block survey) through what has been denoted the serendipity effect [172]. This is principally because high-level vertical block surveys have generally been executed to acquire basic material for (orthophoto)map generation rather than for archaeological purposes. Even then, much valuable information has been extracted from such blanket photography. Also, most of the usual arguments to not fly (or even use) verticals from a block survey sortie (see [117,173–175]) have been countered on many occasions by various authors [10,114,176,177].

Moreover, it is not written in stone that a total area coverage should only be flown at mid-day at high-altitudes by professional survey companies that generate true nadir photographs with overly expensive equipment. It is perfectly feasible to generate verticals using the small, two- to four-seater aeroplanes which are typically used in archaeological aerial prospection by modifying the door or mounting the camera externally (e.g., [178–181]). Fixing a camera to the side of the aircraft for taking vertical photographs was already very common during the First World War [51]. Nowadays, Unmanned Aerial Systems (UASs) will also predominantly acquire vertical still imagery in a total area style with abundant image overlap. The reasons for this are pretty obvious. First, vertical, block-covered footage offers an advantage in mapping, as the induced geometrical distortions are much smaller than those embedded in oblique footage [182]. Second, the illumination changes across the image frame are smaller and the scale is approximately constant throughout [139]. Since the data are by default captured with a high overlap, they are also perfectly suited to create three-dimensional DSMs (see Figure 8B). When acquired from operating heights that surpass allowable UAS altitudes, the high spatial resolution and broad coverage of blanket vertical imaging make them relevant for a holistic view of the landscape, to map extensive geo-archaeological traces as well as for the primary discovery of small, individual archaeological features. Finally, even low-slanting sunlight is not an absolute necessity anymore for recording earthworks or differences in vegetation height. Most orthorectification approaches now automatically generate DSMs [183,184]. These can be used to artificially produce shadow marks in a fast and (depending on the extent of the data set) even interactive way (Figure 8B) [185], while many additional techniques exist to highlight small topographic differences further (see Figure 8C) [186].

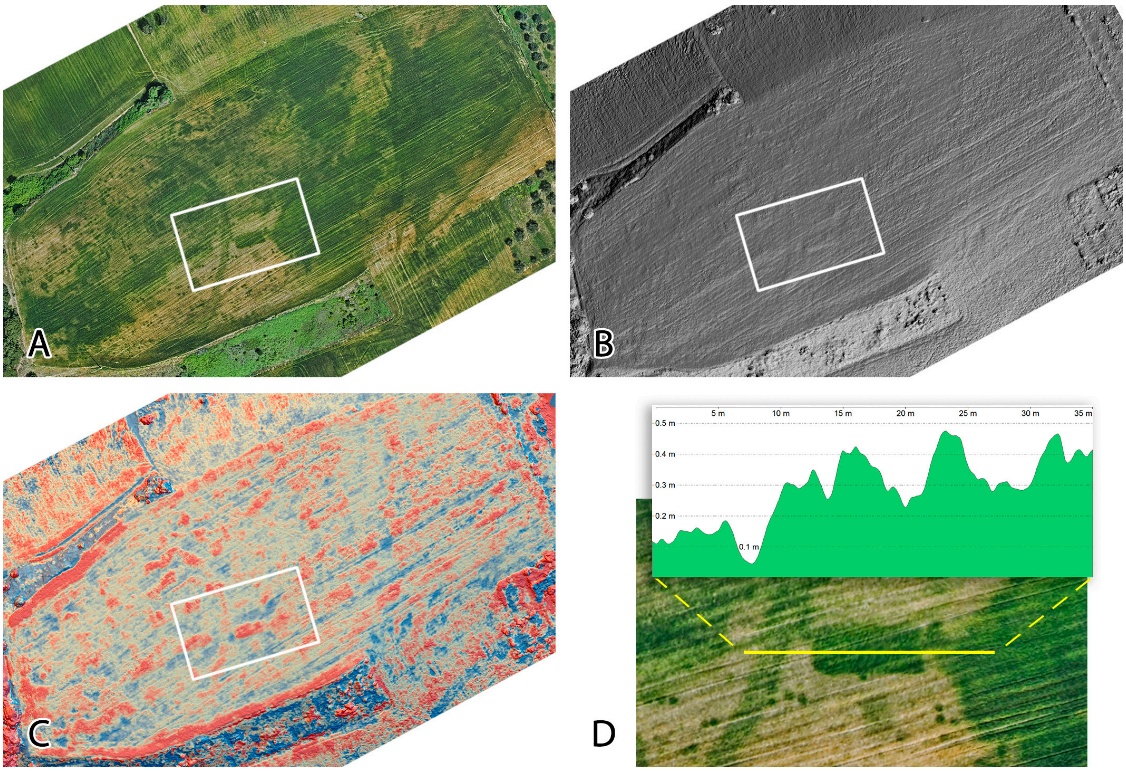

Figure 8. (**A**) Orthophotograph of the Montarice hilltop (Marche, Italy; 43°25′18″N, 13°39′33″E—WGS84) showing many vegetation marks. Although no shadow marks are visible, the next three visualisations clearly indicate differences in vegetation height; (**B**) a DSM with artificially created shadow marks; (**C**) a local relief model (annulus kernel, (45 pixels, 75 pixels)) brings out the tiny differences in vegetation height; (**D**) a zoom of the same scene (its extent is indicated in **A**–**C**) with the height of the crops extracted along the uninterrupted yellow line after computing a canopy height model. More details are mentioned in [186].

Of course, this does not mean that observer-directed flights in favourable light conditions should be discarded. In between total coverage approaches, one can certainly think of a few targeted observed-led sorties to acquire additional image material. However, observer-directed flights as a means to better understand the recorded features or the area under study might make subsequent interpretations of landscape organisation problematic if one assumes that past people also had a similar 'aerial (over)view' concept of the landscape. In contrast, the photographs that are possible with observer-based obliques are also still valid if one flies for artistic satisfaction or documenting standing remains (certainly when those are to be found environments such as deserts; e.g., [187]). However, it is the author's firm conviction that these flights should be rather the exception than the rule.

Though Campana argues to "supplement oblique aerial survey with some form of 'total' recording at those times when archaeological visibility is at its best" [188] (p. 12), he arguably makes a false assumption that archaeological aerial archaeological photographic reconnaissance cannot escape its inherent subjectivity and selectivity. On the contrary, it does not take all that much effort to replace the observer led approach with a reconnaissance strategy involving cumulative total coverage surveys, with or without oblique camera observation angles, executed from the same light aircraft commonly used for archaeological airborne prospection. Of course, a certain amount of subjectivity will always exist (such as choice of pilot, aircraft, flying height, time of data acquisition), but the main data selectivity actors are not that hard to weed out. Maybe one of the key arguments in realising the necessary change in archaeological mindset lies in the fact that information about soil type, hydrology, land use and vegetation cover—which is all extractable from continuous airborne coverage—can even help to detect bias in other data sources [189].

7.2. Multispectral and Portable

It is also deemed of the utmost importance to acquire spectral data in a handful of small, vegetation and soil mark-sensitive spectral bands as well as in the very common broad wavebands of the visible spectrum, since the interpretation of the former will greatly benefit from the latter [11]. Ideally, imagery could be acquired in the green peak at 550 nm (30 nm FWHM), the red edge at 705 nm (30 nm FWHM) and the NIR shoulder at 820 nm (100 nm FWHM). Those three spectral bands have repeatedly been shown to be strongly related to biophysical changes caused by plant stress [190–193]. They are, therefore, well-suited for assessing crop (and by extension vegetation) characteristics, while the combination of the 820 nm NIR band and the 705 nm Red Edge band has already proven its potential in archaeological prospection [156,194,195]. Additionally, the potential information captured in the NIR band is not solely restricted to vegetation marks. Since water heavily absorbs NIR [196] and existing soil moisture differences are often characteristic of soil marks [197,198], discerning the latter becomes easier in the NIR as compared to the visible range. Moreover, all three bands exhibit relatively small anisotropic reflectance effects [199]. This approach also omits the overload of highly correlated spectral data that is characteristic for conventional AIS approaches, while a high spatial resolution can be combined with a high spectral resolution (be it in less spectral bands). To measure the incoming visible spectrum, a normal state-of the-art camera can be flown alongside.

When the imaging solution is also transportable and easy to mount on a variety of light airplanes (e.g., Cessna 152, Cessna 162 Skycatcher, Cessna 172 Skyhawk and Cessna 182 Skylane), repetitive, cost-effective and total coverage airborne survey will become commonplace, offering local researchers the chance to have a high-end imaging system flown at very reasonable costs.

7.3. The Processing and Interpretation Back-End

Although it might seem that the need for the proposed passive optical imaging approach is paramount regardless of the data processing and interpretation pipeline, such drastic developments can not only stay limited to the acquisition phase. The predominant single-imaged based workflows are just too slow and cumbersome to deal with the large amounts of aerial imagery that are constantly generated. As a result, millions of aerial photographs are simply stored in archives where they are at risk of loss or obscurity and their archaeological information cannot (or will not) be exploited efficiently (contributing to another form of bias).

The only solution is to leave the current post-acquisition workflows behind in favour of processing and interpretation pipelines that can deal with a multitude of images at once, thereby saving on the demands for skill, money and time. Given the current failure to do so, the latter three are also often quoted as reasons to stay away from total area coverage [117]. As a result, new georeferencing approaches, radiometry processing algorithms, management structures and interpretation strategies must be conceptualised, tested and implemented, not only to maximise the usability of aerial optical imagery for landscape archaeology but to simply deal with the large amounts of airborne data that will result from the proposed image acquisition approach. Although it is sometimes said that studying a sample with great care might yield more information than studying the complete population [80], advances in data storage, computational power, machine vision and deep learning start to render this argument more or less invalid for these image collections. When the processing and interpretational chains are properly set-up (see also [12,200,201]), dealing with several thousands of images should not be much more of a burden than dealing with a few hundreds of them.

Although the technology is available, realising all these aspects will not come easy because the major challenge lies in the creation of a new methodological, analytical and interpretational mindset. Since this paper does not want to suggest that a blind collection and accumulation of aerial data is the way to go, this new data collection strategy must go hand in hand with (the already partly ongoing) renewed practical and theoretical reflections on the detection, identification, typological and chronological classification, perception and interpretation of landscape features [18,54,68,101,168,202–207]. These considerations remain vital because archaeology still falls short of realising the full potential that digital data have to offer [208]. However, instead of looking for the optimal solution according to one dogmatic paradigm, it is best to accept that these aerial imaging products also have their limits. As such, this paper advocates the vision that archaeologists should try to combine the complementary strengths of different theoretical and analytical methodologies while sticking to a healthy amount of source-criticism and scepticism. Only then can the combination of computing power and this new digital imagery provide new archaeological insights, regardless of the theoretical framework.

8. Conclusions

Archaeologists need to reflect on the ever-expanding array of specialised topics and methods to continue their integration and to combine their different strands of thinking. In most of the cases, archaeologists try to build data by systematically observing the preserved archaeological record. The combination of any pre-existing intellectual perspective and the research problem ultimately—but often unconsciously—determine which observations are made. Finally, the data collection tool that is used determines the exact nature of these observations. This paper has taken a reflexive approach to how archaeologists with different (but often unknown) theoretical convictions have been acquiring passive optical imagery from the air. Starting from the concept of landscape archaeology, the principles of archaeological remote sensing and the need for bias reduction when sampling the archaeological record, the author has tried to assess all passive airborne optical imaging approaches in terms of eight essential characteristics, which all bear the potential to increase or decrease the subjectivity and bias in the acquired image set.

Although archaeological optical imagery is never an 'objective' or theory-neutral dataset, it has been shown that the amount of data favouritism and partiality can easily be significantly reduced. This reflection is not to diminish the importance of data collection strategies used so far. Even though the observer-led passive airborne imaging approach of the early years was entirely appropriate, as "the imperative then was to record as many previously unknown monuments as quickly as possible" [209] (p. 65), this essentially site-based methodology seems nowadays at odds with many current core conceptions of landscape archaeology. However, also the conventional multi- and hyperspectral imaging approaches have proven to be inherently flawed, be it by their sampling design, cost, instrument availability or processing complexity. As a result, they also cannot prevent highly biased data collection and usage.

Can any form of meaningful insight about the past be obtained at all if biased remote sensing methods continue to generate some of the key datasets in landscape archaeology? How can one argument in a coherent way if the data at hand do not allow for a proper evaluation of the argumentation? Instead of considering possible answers to these questions, this paper started from an intellectually-integrative approach to landscape archaeology to propose a new technological-methodological data acquisition strategy. This attempt is based on assumptions that (1) any lack of understanding all inherent airborne data flaws will be prone to erroneous and unsupportable conclusions and that (2) remote sensing will become ever more integral to the process of understanding the human past and that (3) to "extract the most complete understanding of the settlement dynamics of an extensive territory requires the application of special field methods" [52] (p. 23).

One might say that the attention for the method and the need to exhaustively and cumulatively collect imagery exemplifies a positivistic, empirical approach to archaeology. However, the need to optimise data collection in various dimensions does not hamper its interpretation. Although this paper advocates in true processual style a standardisation of practice and aims at systematic, repeatable imaging surveys with better sampling characteristics, it does not advocate a separation between observation and interpretation, between analytical and interpretive archaeologies. The attention given to the analytical method of aerial survey does not prevent an interpretative approach to the data, nor does it mean that one will automatically better know the past or that cognitive objectivity is assumed.

This ties directly into the question of the fitness-for-purpose of aerial imaging in landscape archaeology and the seemingly logical follow-up argument that there is a need for an initial broad-brush landscape characterisation approach to determine those portions of the study area for which passive airborne imaging has archaeological potential [210]. First, a major part of this argument stems from the fact that broadband photography in the visible spectrum has always been the *de facto* way of aerial imaging. This approach does indeed often fail in less-than-optimal circumstances (see Section 5). Despite the fact that Taylor already wrote forty years ago that "Continuous reconnaissance, using new techniques, over areas normally regarded as poor or unrewarding is a basic need for future field archaeology" [211] (p. 140), unrewarding or 'unresponsive' zones have seldom been targeted with more specific imaging approaches such as those presented in this paper.

Second, this type of criticism regularly contrasts aerial optical imaging with geophysical approaches and excavation techniques (e.g., [17]), both of which are often considered to deliver uniform data sets that provide almost absolute knowledge about the archaeology hidden within the soil matrix (excavations even more so that geophysics [212]). However, the chemical and physical properties of the soil with its embedded archaeological residues as well as the sensor characteristics both limit all three approaches to landscape investigation. It is a well-known but often neglected fact that excavations might fail to uncover archaeological features that are revealed by both remote sensing and geophysics [213,214]. Although this situation might cause serious incomprehension among many archaeologists, it is not difficult to understand that a geophysically measured contrast (such as an increase in magnetic susceptibility) does not have to translate into a colour difference (which is the contrast on which the human visible system or a standard photographic camera relies).

On the other hand, geophysical sensors might be unable to record archaeological features in certain conditions. For instance, high topsoil salinity or wet and clayish conditions can render ground-penetrating radar almost useless. As a result, archaeological features might show up in aerial photographs but not in geophysical datasets [215,216]. Since both excavations and geophysical methods can only recover some specific aspects of the preserved archaeological record, their data are thus by default also incomplete. While excavations and geophysical prospection usually have a better reputation regarding their archaeological effectiveness and data consistency, they thus also suffer from the uncontrollable biases that characterise passive airborne optical imaging.

Even though the number of data representativity issues might indeed be greater for airborne imaging, one should never consider the absence of any archaeological evidence as proof of archaeological absence for any of these three methods (or many other prospection methods for that matter). Despite the inherent biases in their recovered archaeological record, both excavation and geophysical survey oriented archaeologists generally accept that dense sampling of large, continuous areas is key to properly understand what is going on at a site or landscape level [217–219]. This paper followed the same reasoning. Only when the sampling is done properly, one can combine the aerial imagery with colluvial, alluvial and aeolian records [149] or other data sources to assess and truly understand the biases imposed by topography, environmental factors and land uses. Otherwise, any assessment of fitness-for-purpose of the aerial imagery for answering particular landscape archaeology questions or any broad-brush landscape characterisation to matching survey methodology to local context seems the wrong way around.

Since the proposed approach has the potential to remove many of the major and controllable data gathering biases, the resulting image sets should enable holders of rival theories to agree on the fact that these data are archaeologically useable. Finally, imagery collected in such a non- (or less) selective way can also be of use to subsequent studies that might have largely different scopes. Or it can facilitate data examination with oppositional analytical and interpretative approaches. In this way, it is hoped that we can build, in combination with many other data sets, potentially novel, more robust and richer understandings of the landscapes that are diachronically and synchronically constituted by the reciprocal relationships between human and their environment.

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