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An assessment of high temporal frequency satellite data for historic environment applications. A case study from Scotland

Ciara N. McGrath[1] | David C. Cowley[2] | Sine Hood[2] | Sheila Clarke[2] | Malcolm Macdonald[3]

[1]Department of Mechanical, Aerospace and Civil Engineering, University of Manchester, Oxford Road, Manchester, M13 9PL, UK

[2]Historic Environment Scotland, Edinburgh, UK

[3]Applied Space Technology Laboratory (ApSTL), Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, UK

Correspondence
Ciara N. McGrath, Department of Mechanical, Aerospace and Civil Engineering, University of Manchester, Oxford Road, Manchester M13 9PL, UK.
Email: ciara.mcgrath@manchester.ac.uk

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Abstract

This paper assesses the value of high temporal frequency satellite data with various spatial sampling resolutions for multi-scalar historic environment survey and management use cases in Scotland, specifically for broad-brush landscape characterisation, for monitoring the condition of monuments and for the discovery of otherwise unknown sites. Dealing with a part of the world where applications of satellite imagery are almost entirely unexplored, this study takes a real-world approach, which foregrounds the purpose at hand rather than presenting a case study from an optimal setting. The study highlights the importance of detailed imagery to support interpretation in some instances, and the challenges of obtaining time-critical optical imagery in a part of the world that experiences significant periods of cloud cover. The real-world availability of data in such settings is assessed, highlighting that even with daily revisits, useable imagery cannot be guaranteed. The implications of current and past tasking patterns for availability of high-resolution data now and in the future are discussed. The study identifies the complementary roles that satellite imagery can fulfil, while identifying the limitations that remain to fuller applications of such data, in a study that will be relevant to many parts of Europe and beyond.

KEYWORDS
aerial photographs, archaeological survey, heritage monitoring, PlanetScope, satellite imagery, SkySat

1 | INTRODUCTION

This paper assesses the value of high temporal frequency satellite data with various spatial sampling resolutions for archaeological and historic environment survey and management purposes in Scotland, a part of the world where such applications are almost entirely unexplored (i.e., Winterbottom & Dawson, 2005). The work reported on here is a contribution to a broad-based assessment of remote sensing data and methods for national-scale archaeological survey and heritage management (see Banaszek et al., 2018; Cowley et al., 2020) that includes consideration of satellite data sources (e.g., McGrath et al., 2020). The approach taken aims to explore the relationships between the character of archaeological remains and landscapes, their proxies in satellite imagery and a range of heritage purposes. This supports the remit of Historic Environment Scotland (HES), as the lead publicly funded body for the historic environment, which includes identifying, recording, understanding, interpreting and managing the historic environment. There is an expectation that the findings should have direct implications to European regions of similar geography and climate, and more broadly to archaeological and historic landscape applications of satellite data.

Globally, satellite data have been widely applied to archaeological site detection (e.g., Agapiou et al., 2013; Alexakis et al., 2009; Altaweel, 2005; De Laet et al., 2007; Keeney & Hickey, 2015; Lasaponara & Masini, 2007, 2011; Luo et al., 2019), often in arid regions where many archaeological sites are large and/or high-contrast (e.g., Agapiou et al., 2013; Beck, 2007; Casana, 2020; Hammer et al., 2022). The climate, landscape character and forms of archaeological remains in Scotland, and similar areas of north-west Europe, present a challenge for the use of satellite remote sensing data as components of sites are often small and/or seasonally visible as crop proxies (e.g., Cowley, 2016; Gojda & Hejcman, 2012; Maxwell, 1983; RCAHMS, 1994). The increasing spatial resolution and temporal frequency of satellite data offers considerable potential for such applications and to address limitations in traditional approaches to archaeological survey, which suffer from limited scale of coverage and revisit intervals. This paper reports on an assessment of PlanetScope and SkySat satellite data, as an example of the 'next generation' of high spatial resolution and temporal frequency satellite data.

PlanetScope and SkySat are constellations of spacecraft operated by Planet Labs Inc. (Planet, 2021), and the data used in this work were provided through the 2020 European Space Agency Announcement of Opportunity for Planet SkySat and PlanetScope data. The work reported on here aims to provide a 'real world' assessment of the utility of the data, rather than a demonstration of potential based on best-case scenarios. This makes use of visual assessment as the primary approach for the purposes of direct comparison between types of imagery within an established workflow, while recognising the benefits of a range of image processing techniques (e.g., De Guio, 2015; Luo et al., 2019), which are otherwise not dealt with here.

1.1 | PlanetScope and SkySat

The PlanetScope constellation, at the time the majority of satellite data for this work was acquired (April–August 2020), comprised approximately 100 3U CubeSat spacecraft (Johnstone, 2022). These spacecraft were launched in multiple batches over time and have varying capabilities. All PlanetScope spacecraft operate in sun-synchronous orbits at altitudes between 450 and 580 km. This provides coverage between ±81.5° latitude with an equator crossing time of between 9:30 and 11:30 AM (Planet, 2021). The spacecraft instrument is an imager with a minimum of four bands ranging from 455 to 888 nm and providing a ground sampling distance (GSD) at nadir of 3–4.2 m, depending on the altitude and generation of spacecraft. PlanetScope aims to provide high temporal frequency, imaging each point on Earth's landmass at least once per day (Boshuizen et al., 2014; Planet, 2021). However, the actual image capture frequency can vary by geographical location (Roy et al., 2021), and the usability of the imagery will be dependent on cloud cover.

At the time the majority of satellite data for the work was acquired (April–August 2020), the SkySat constellation comprised 13 active spacecraft. Three additional spacecraft were launched in June 2020, and three more in August 2020, but they were not commissioned and active in time to contribute data to this project. The SkySat spacecraft orbit at approximately 500 km altitude (Planet, 2021) and provide a GSD of 0.58–0.86 m in the panchromatic band and 0.72–1.0 m in the four multispectral bands (450–900 nm), depending on the altitude and generation of spacecraft. All SkySat products are processed to provide a pixel size of 0.5 m when orthorectified. Each SkySat spacecraft is noted as having a 4 to 5-day revisit time. However, this revisit time relies on the ability of the spacecraft to slew and target areas of interest off-nadir, meaning that not all points on the Earth can be captured. As such, the SkySat constellation operates a tasking model, in which users can request acquisition of imagery over specific areas of interest in a given time period. Thus, the availability and usability of data from the SkySat system depend on factors including cloud cover and sun angle at time of acquisition, obliqueness of view, spacecraft orbit properties, tasking availability and (in the case of archival imagery) historical tasking patterns.

1.2 | Historic environment applications

The assessment of the SkySat and PlanetScope satellite data presented in this paper focuses on three main historic environment applications undertaken by Historic Environment Scotland (HES), which are typical of activities that may be undertaken by national heritage organisations:

1. landscape-scale characterisation and land-use change detection;
2. condition monitoring of cultural heritage sites; and
3. detection of otherwise unknown archaeological monuments.

These applications reflect a multi-scalar concern with landscape both to understand its archaeological and historical dimensions and to analyse and document change. Considering monitoring of landscape-scale land-use change for its direct implications for the historic environment, there are no mechanisms in place to achieve this, in Scotland or globally. Scotland has a national broad-brush landscape mapping, the Historic Land-use Assessment (HLA), compiled at a scale of 1:25 000 to characterise both the contemporary landscape and the historic land-use it contains (HES, 2021; Watson & Dixon, 2018). Building on this national map, work is underway within HES both to consider how to refresh this mapping in future drawing on heavily automated processes and to develop a landscape monitoring tool that detects landscape-scale change in the historic environment. In this context, the assessment of available satellite data for this purpose will be vital to support policy and strategic responses to drivers such as climate change, land-development and environmental protection.

Monitoring of cultural heritage sites in Scotland is focussed on just over 8000 designated monuments. The approach taken since 2013 applies a mixed economy of visits on the ground by field officers and analysis of aerial photographs, with a revisit interval of five or more years. Both targeted oblique aerial imagery taken especially for monitoring from a light aircraft and general purpose aerial orthophotographs are used to complement ground visits. Such imagery has a GSD of 0.25 m and better, allowing the detection of issues such as damage by stock and other animals (e.g., rabbit burrows). Freely available Sentinel data have been used to establish the timing of gross damage at designated sites, though without the level of detail used for ongoing site condition monitoring to assess a wider range of issues, such as animal burrows, at a much finer level of detail. Satellite imaging is being explored to assess the potential to significantly improve revisit frequencies if required and to provide a wider context to the monuments being monitored. This would directly influence national conservation programmes and provide a proof of concept applicable to, and with value for, nations across Europe and beyond.

The use of remote sensed data to support archaeological and landscape mapping is well-established in Scotland, drawing on field observation, aerial reconnaissance, examination of archival aerial imagery and applications of lidar data (Cowley, 2016; Cowley et al., 2020; Dunbar, 1992; Geddes, 2014; RCAHMS, 1994, 1997, 2009). However, the use of satellite data for the detection of archaeological monuments and the mapping of landscapes is nascent. In large part, this is because available satellite data do not have the spatial resolution to be useful, whereas the rich tradition of using other data sources to good effect has reduced any motivation to explore further data sources. However, there is a recognition that the increasing spatial and temporal resolution of satellite imagery represents a step-change and requires systematic assessment for its contribution to the future development of survey practice, whereas satellite data outputs such as soil moisture are recognised as having value for survey planning.

1.3 | Objectives and scope of assessment

The objectives of the work presented here are to assess the suitability of PlanetScope and SkySat imagery for the historic environment applications listed above, namely, (a) landscape characterisation and change detection assessment on a national scale; (b) monitoring the condition of known archaeological assets; and (c) detection of buried archaeological and cultural heritage sites.

To address these objectives, the PlanetScope and SkySat data were assessed for temporal frequency of coverage (Section 3), the ease and accuracy with which land-use changes, which have implications for cultural heritage sites, could be determined (Section 4.1), the suitability for condition monitoring of designated cultural heritage sites (Section 4.2) and the ease and accuracy with which proxy indicators of archaeological features (such as crop and soil marks) could be identified (Section 4.3). These are all issues that have implications beyond Scotland in other regions with similar climates, land-use and geology, including much of continental Europe.

2 | PLANET DATA

Two types of data were available as part of the ESA and Planet sponsored project, which can be characterised as 'Archival' and 'Tasked'. Archival data are imagery that has been collected in the past either through regular satellite operations or through directed tasking requests. Due to the defined collection patterns of the PlanetScope spacecraft, the archival ~3–4 m GSD PlanetScope data are generally regularly distributed both temporally and spatially. For the <1 m GSD SkySat imagery, the archival data set is irregular and dictated by previous tasking activities. Selections from available archival datasets were made primarily considering the availability of imagery over the areas of interest, time of acquisition (and how this aligned with the project goals [e.g., likelihood to reveal crop proxies]) and the usability of the data in terms of cloud cover, haze and area coverage. The tasked data were acquired by the SkySat constellation in response to our specific requests. In this case, a request was submitted in advance, defining the area of interest and temporal frequency of desired imagery collection.

The PlanetScope data product selected for use in this assessment was the *PlanetScope Ortho Scene*. This product is provided as a radiometrically and sensor corrected GeoTIFF that has been orthorectified and resampled at 3 m. The SkySat data product selected for use in this assessment was the *SkySat Ortho Scene*. This product is provided as a radiometrically and sensor corrected GeoTIFF that has been orthorectified. These are both categorised by Planet as Level 3B products. Level 1B *Basic* products are also available from Planet. These allow the user to process the imagery themselves, using methods of correction and orthorectification that are most suitable for the subsequent data usage. This could enhance the quality of the final imagery for assessment purposes but requires a skilled remote sensing expert to ensure correct handling. As such processing falls outside the standard assessment pipeline, it was determined that the Level 3 data were most appropriate for this study.

2.1 | PlanetScope

Within the framework of this project, seven areas were defined to investigate the PlanetScope data. Four areas of primary interest (Figure 1, left) were defined with reference to case studies in a Joint Nature Conservation Committee (JNCC) coordinated proof of concept for a web-delivered Landscape Monitoring application (Lightfoot et al., 2021). The JNCC project aimed to enable users to detect and track change over time, based on automated analysis of a five-year Sentinel-1 and Sentinel-2 time series, from which indices for surface water and for vegetation productivity, structure and water content were generated.

Two archival PlanetScope images were selected from the summer of 2018 for each of the identified areas of interest. One acquisition was in May, and one in July to allow for seasonal differentiation, supporting an assessment of their suitability for broad-brush landscape characterisation and monitoring. Three areas of secondary interest (Figure 1, right) were also selected to cover ground that has a high likelihood for buried archaeological features to be revealed through vegetation proxies (cropmarking) in dry conditions. One image from early July 2018 was selected for each of these areas, targeting a period when widespread archaeological cropmarking was detected

FIGURE 1 (L) Locations of primary PlanetScope areas of interest: 1. Gatehouse of Fleet, 2. Flanders Moss, 3. Cairngorms and 4. Caithness. (R) Locations of secondary PlanetScope areas of interest: 5. Kelso, 6. Fife and 7. Angus. *Source*: © Planet Labs Inc. 2021

TABLE 1 PlanetScope data selected for assessment

AOI no.	AOI	Centre coordinates	Date of acquisitions
1	Gatehouse of Fleet	54.88°N	28 May 2018
		−4.19°W	01 July 2018
2	Flanders Moss	56.13°N	28 May 2018
		−4.16°W	05 July 2018
3	Cairngorms	57.08°N	28 May 2018
		−4.01°W	04 July 2018
4	Caithness	58.25°N	27 May 2018
		−3.57°W	03 July 2018
5	Kelso	55.53°N −2.45°W	01 July 2018
6	Fife	56.27°N −3.17°W	07 July 2018
7	Angus	56.63°N −2.87°W	06 July 2018

Abbreviation: AOI, area of interest.

during traditional observer-directed aerial reconnaissance in a light aircraft. While the 3–4 m GSD of the PlanetScope imagery was not expected to directly reveal archaeological sites (i.e., because of the small dimensions of most expected archaeological features), it was assessed for its potential to provide broad patterns of vegetation (mainly arable crops and grass) condition and its likelihood of producing archaeological cropmarking.

Data selected for each area of interest (AOI) are given in Table 1, along with the approximate latitude and longitude of the central point and the date of acquisition. Images were selected manually to meet the desired criteria, as well as minimising cloud cover and haze, and maximising coverage of the AOI. Suitable data for all selected areas were available in the PlanetScope archive.

2.2 | SkySat data

Two sets of SkySat data were assessed, the first comprising archival imagery (Section 2.2.1), and the second imagery whose collection was tasked to our requirements (Section 2.2.2).

2.2.1 | Archival SkySat data

Archival SkySat data for two regions were obtained for assessment (Figure 2; Table 2). One image was selected from April 2020 for both the Ayr and Border regions, and one additional image was selected from July 2021 for the Ayr region. These areas were selected for their

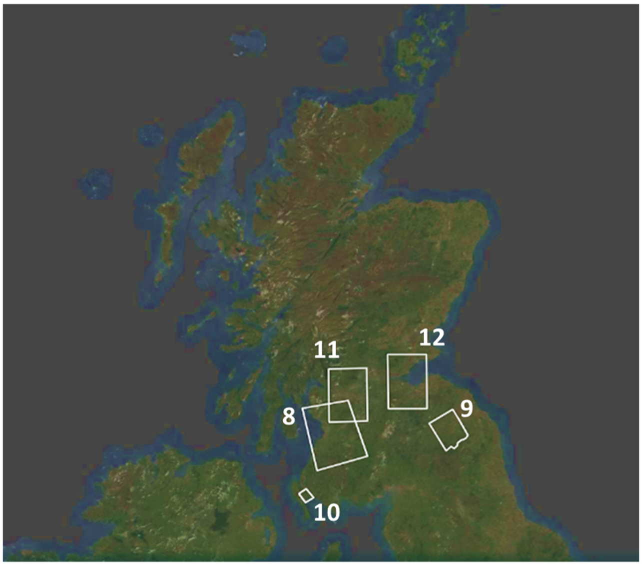

FIGURE 2 Locations of SkySat areas of interest: 8. Ayr, 9. Borders and 10. Stranraer. Also shown are locations used for data availability assessment: 11. Glasgow and 12. Edinburgh. *Source*: © Planet Labs Inc. 2021

TABLE 2 SkySat archival data selected for assessment

AOI no.	AOI	Centre coordinates	Date of acquisitions
8	Ayr	55.49°N	19 April 2020
		−4.54°W	24 July 2021
9	Borders	55.48°N −2.42°W	25 April 2020

Abbreviation: AOI, area of interest.

interest to HES for monitoring of designated archaeological monuments, with the Ayr area also having potential for cropmarking to reveal buried sites.

2.2.2 | Tasked SkySat data

In order to assess the potential of tasked satellite imagery collection to replace observer-directed reconnaissance in light aircraft, a tasking request was placed with Planet on 24 June 2020 to acquire one image per week during July 2020 in the area around Stranraer in southwest Scotland (AOI 10, Figure 2). This is an area that has been highly productive of archaeological cropmarking in the past (Cowley & Brophy, 2001). In order to fulfil this request, Planet tasked the SkySat constellation to acquire multiple images over the area of interest on almost every day in July. The five most suitable images were selected from those acquired (Table 3).

TABLE 3 SkySat tasked data selected for assessment

AOI no.	AOI	Centre coordinates	Date of acquisition
10	Stranraer	54.88°N −4.94°W	10 July 2020
			18 July 2020
			20 July 2020
			21 July 2020
			28 July 2020

Abbreviation: AOI, area of interest.

3 | SATELLITE DATA AVAILABILITY ASSESSMENT

The assessment of data availability is a crucial first stage to consider the temporal frequency with which data considered suitable for the objectives described in Section 1.3 could be acquired from the PlanetScope and SkySat constellations. Specifically, objectives such as prospection for sites revealed by vegetation proxies are time dependent and may vary in the timing of visibility from area to area depending on cropping and local weather patterns. Data availability assessment is thus a matter of not only assessing revisit intervals, for which the satellite's field of view can be a factor, but also considering incidence of cloud cover.

Cloud cover is a particular challenge in Scotland, which is dominated by an Atlantic weather system that produces very variable conditions. For example, during 2020, the Stranraer area (AOI 10, Figure 2) experienced below average sunshine and above average rainfall and temperature when compared with the 1981 to 2010 averages (Met Office, 2020). Taking the cloud measured at Dundrennan weather station to the east of Stranraer (Lat: 54.8°, Lon: −4.0167°) during July 2020 by way of example, 73% of hourly cloud cover measurements during daylight hours are fully cloudy (7–8 octas). A further 14% of measurements are partially cloudy (3–6 octas), and just 13% of measurements are clear (0–2 octas; Figure 3). This implies that, on average, roughly one in four optical images taken by a satellite of this region should have cloud free portions, though these images may not be evenly distributed over time. As seen in Figure 3, the periods from 2nd to 5th July and 13th to 17th July 2020 are almost entirely cloudy.

Cloud is thus a significant factor limiting availability of imagery for Scotland that is evident when using the Planet Data Explorer image browser. This is confirmed by a UK-wide assessment of Sentinel imagery for a Landscape Monitoring application (see Section 2.1 above) where availability of Sentinel-2 imagery for selected areas of interest between October 2016 and June 2020 varied from 35 to 83 scenes per location (Lightfoot et al., 2021, 6). In one study area in England, there was no cloud-free Sentinel-2 imagery from 05 August 2018 to 26 February 2019, limiting the use of optical indices to monitor the aftermath of a large moorland fire (Lightfoot et al., 2021, 17).

The Planet Data Explorer (https://www.planet.com/products/explorer/) allows visualisation and downloading of PlanetScope and

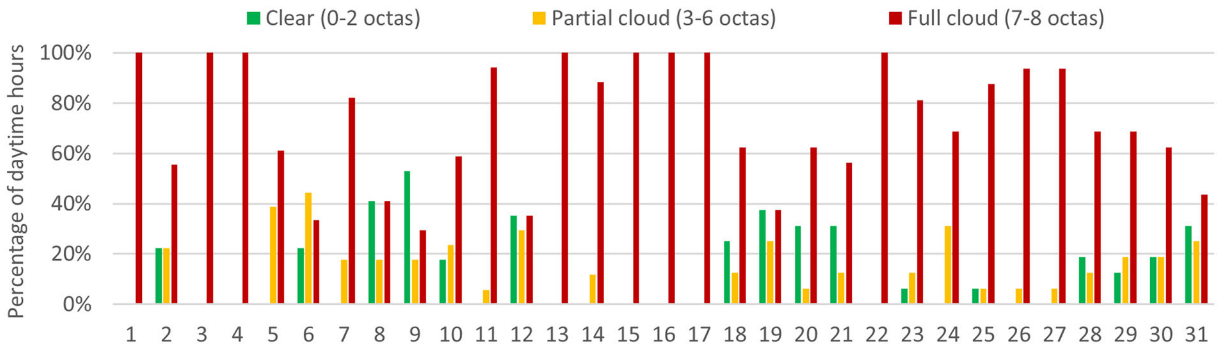

FIGURE 3 Percentage of daytime hours each day classified as clear (0–2 octas), partial cloud (3–6 octas) and full cloud (7–8 octas) for Dundrennan through July 2020. *Source*: Met Office (2012)

TABLE 4 PlanetScope data availability assessment results

No.	AOI	Total images	>50% AOI	<50% cloud	Useable
1	Gatehouse of Fleet	85	57	26	13
2	Flanders Moss	97	62	31	6
3	Cairngorms	114	83	32	14
4	Caithness	101	81	38	14
5	Kelso	111	82	34	18
6	Fife	92	72	34	14
7	Angus	116	84	36	18

Abbreviation: AOI, area of interest.

SkySat data. Data can be filtered by cloud cover, though in many cases haze or small, dispersed clouds are not identified by the automated filter. Thus, in order to assess data availability, two stages of filtering are required. In the first stage, those images flagged by the Planet Data Explorer filter as having >50% cloud cover were excluded. In the second stage, those images considered useable were manually identified from the remaining dataset. In the case of the PlanetScope data, an additional layer of pre-filtering was done to include only data that cover >50% of the area of interest.

3.1 | PlanetScope data

The data availability of AOIs 1–7 (Section 2.1, Figure 1) was examined for the period from 01 April 2020 to 31 August 2020 to identify the total number of images available, the number of images covering >50% of the AOI and those with <50% cloud cover. From those images covering >50% of the AOI and with <50% cloud cover, a manual assessment identified those images judged to be useable (Table 4). For all regions except Flanders Moss (AOI 2), approximately 15% of the total images acquired were found to be useable, corresponding to a useable image on approximately 10% of the 153 days from 01 April 2020 to 31 August 2020 (inclusive). Flanders Moss (Figure 1, left, AOI 2) had significantly worse data availability, with just 6% of images useable on 4% of days.

3.2 | SkySat archival data

The data availability of AOIs 8 and 9 (Section 2.2.1, Figure 2) was examined for the period from 01 April 2020 to 31 August 2020. As with the PlanetScope data, for each AOI, the total number of images available was assessed, from which the number of images, which covered >5% of the AOI, was identified. This small coverage requirement was selected to account for the relatively discrete area covered by a single SkySat acquisition compared with the large areas under consideration. Of these, those identified as having <50% cloud cover were identified. Finally, from those remaining images, useable ones were manually identified (Table 5). For comparison, a similar sized area around the cities of Glasgow and Edinburgh was also examined (AOIs 11 and 12, Figure 2). The variation in total images, and those covering more than 5% of the AOI, illustrates the influence that historic tasking priorities have on the availability of archival data. However, for Scotland at least, the impact of cloud remains a dominant issue with similarly few useable images available for all regions (Table 5).

3.3 | SkySat tasked data

The tasked element of the project specified one image to be collected of the Stranraer area (AOI 10, Figure 2) each week in July 2020 using the SkySat spacecraft constellation. This aimed to provide imagery to

TABLE 5 Archival SkySat data availability assessment results

No.	AOI	Total images	>5% AOI	<50% cloud	Useable
8	Ayr	34	7	3	2
9	Borders	17	3	1	1
11	Glasgow	32	30	7	2
12	Edinburgh	8	3	1	0

Abbreviation: AOI, area of interest.

assess the development of cropmarking in arable crops and to mimic the intervals at which traditional observer-directed light aircraft aerial reconnaissance might revisit an AOI. During the month of July, the SkySat constellation collected 150 images of the region. Of these, 26 had <50% cloud cover, equating to just 17% of images, and some of these were collected on the same day. Because the images were to be used for time varying purposes (i.e., the assessment of change in crops and the identification of archaeological cropmarking), multiple images collected on the same day are of limited value. Thus, while images were collected on 21 days throughout July, images with <50% cloud cover were only available on 5 days.

4 | USE CASES

The discussion above has defined some of the basic characteristics of the satellite datasets under assessment, as a prelude to a consideration of their suitability for the three main historic environment applications at HES.

4.1 | Landscape-scale characterisation and land-use change detection

Landscape-scale characterisation is broad-brush, aiming to deal with large regions or entire countries. This necessitates a generalising approach in which detail is sacrificed in pursuit of the over-view (Fairclough et al., 2018; Fairclough & Herring, 2016; Millican et al., 2017; Olwig et al., 2016). Thus, in Scotland, the HLA, which has mapped the historic origins of land-use within a framework of the contemporary landscape (Watson & Dixon, 2018, 248–50; http://hlamap.org.uk/content/about-hla), was compiled with a minimum unit size of 1 ha against a mapping background of 1:25 000. While the HLA is coarse-grained mapping, it nevertheless benefited from detailed views of the landscape, especially through aerial photographs at a variety of capture scales up to 0.25 m GSD. Building in part on this existing national mapping, the aspiration to develop landscape-scale (i.e., nationally or at least regionally) change detection also requires a similar approach to minimum unit size underpinned by an understanding of the role that detailed imaging plays in creating broad-brush mapping. While we have an expectation that future developments of characterisation datasets and change detection will rely to a degree on automated approaches, for present purposes, the satellite data were assessed visually in a geographic information system (GIS) environment by a member of HES staff who had worked on the HLA for many years. In this assessment, building on experience of past mapping from aerial photographs, the basic requirements are to be able to differentiate types of contemporary land-use and to see features that contribute to characterising the landscape in adequate detail (e.g., field boundary types).

Unsurprisingly, all the imagery proved useful for this type of broad-brush landscape assessment for which the minimum mapped parcel size is 1 ha. For the 3–4 m GSD PlanetScope data, the main forms of land-use can generally be identified (Figure 4). An experienced interpreter will be able to characterise land-use from the PlanetScope imagery, though it is readily apparent how the detail of the aerial orthophotograph will be helpful, for example in classifying different forms of woodland. However, the ability to deal with more complex mosaics of land-use and vegetation cover lessens as the confidence in interpretation diminishes with reduced clarity of the imagery. We note that such issues would be greater for less experienced interpreters, whose confidence in their interpretations will be supported by the ability to see detail in images with some clarity. Thus, while the minimum unit size for landscape-scale work may be 1 ha at a mapping scale of 1:25 000 (for example), the interpretation of features and surface textures will often require very much closer observation of imagery. This represents a very real limitation on the utility of the PlanetScope data for anything other than very generalised broad-brush mapping.

Using SkySat imagery, an experienced photo-interpreter would have no problems visually identifying vegetation type and other general landscape characteristics. However, because the current standard benchmark for such work is 0.25 m aerial orthophotographs, which provide good visible detail, the relative lack of definition in the SkySat imagery is noticeable to the interpreter (Figure 5). The drift in GSD towards off-nadir parts of images exacerbates this issue with noticeable degradation in the crispness with which landscape texture and features are defined. Whereas viewing imagery at scales such as 1:10 000 can provide adequate definition in some cases (Figure 5), often imagery may require inspection at scales of up to 1:1000 in order to see detail that may be crucial to confident interpretation. In these cases, the differences between the SkySat imagery and the 0.25 m GSD aerial orthophotographs become more evident. In an example from the Ayr AOI 10 (Figure 5), the SkySat image does not provide enough clarity to identify with certainty the form of land-use in two of the three visible field parcels. While regularly spaced vehicle

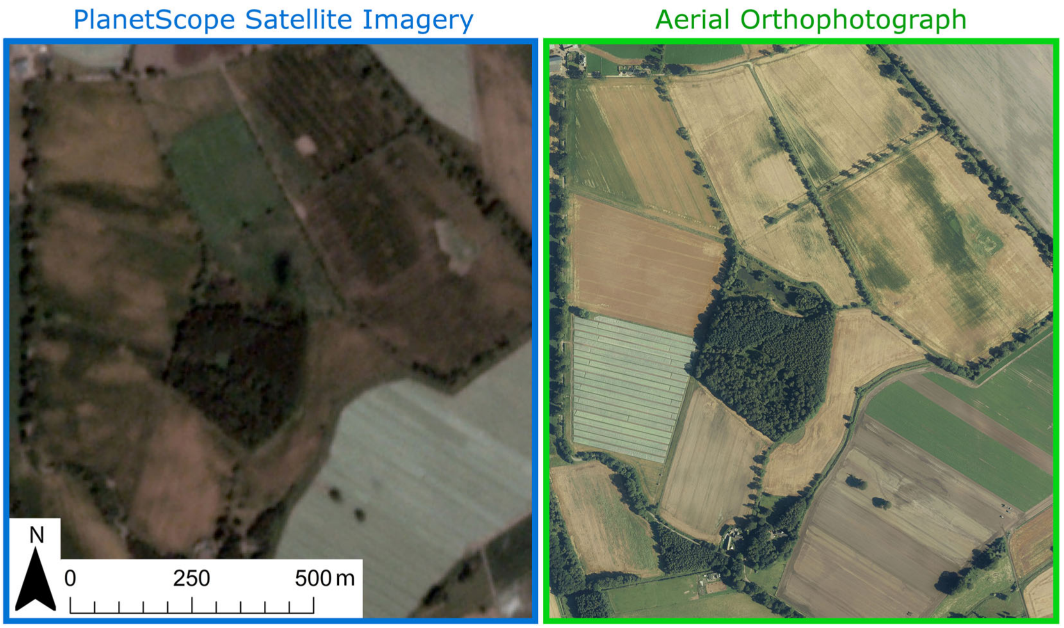

FIGURE 4 Comparison of PlanetScope imagery (left, July 2018) and 0.25 m ground sampling distance (GSD) aerial orthophotograph (right, 2020) for an area in the Howe of Fife (AOI 6; Lat: 56.26°, Lon: −3.18°). Note that these images are not co-temporal. The PlanetScope imagery reveals aspects of crop condition, which would be useful to deploying observer directed aerial reconnaissance if it was available on a weekly or bi-weekly basis (see Section 4.3). *Source*: PlanetScope (left): © Planet Labs Inc. (2020); Orthophotograph (right): © Bluesky International Limited & Getmapping Plc. (2020)

tracks are evident and indicate some form of agricultural practice, it is the 0.25 m GSD aerial orthophotograph (Figure 5, bottom right) that allows a young coniferous plantation (perhaps for Christmas trees) to be identified. Such issues are exacerbated by haze.

This comparison of SkySat imagery with the standard aerial orthophotograph illustrates the step changes in the confidence of visual interpretation due to visible detail. This is an entirely unsurprising observation but is made here with reference to a step from 0.75/0.81 m GSD to 0.25 m GSD. In many cases, this is a crucial difference in managing uncertainty of interpretation, which will especially be the case with less experienced individuals. This also makes an important point about the relationships between scale of imagery (in this case expressed as GSD) and the capacity to see (or resolve) details (Lillesand & Kiefer, 2000; see Cowley et al., 2013, 24–5 for a discussion of this issue). This is an important consideration as resolution can be easily ignored when working with digital raster datasets in a GIS environment where traditional concepts of scale may seem irrelevant (Cowley et al., 2020, 110–12).

4.2 | Condition monitoring

The role of satellite data for monitoring heritage across the globe is well-established, often in the context of identifying looting and urban development that is damaging archaeological sites and landscapes (e.g., Agapiou et al., 2017; Masini & Lasaponara, 2021; Tapete & Cigna, 2019). A more specific requirement for Historic Environment Scotland is fulfilling its obligations to monitor the condition of over 8000 monuments that are designated (scheduled) as being of national importance (HES, 2018). This is approached through a combination of ground visits and inspection of aerial photographs to identify issues and encourage positive management (Hall, 2020). For remotely monitoring condition of ancient monuments, detail can be paramount, and the current products used for this are general purpose 0.25 m GSD aerial orthophotographs and ~0.10–0.15 m GSD aerial photographs taken from a light aircraft specifically for the purpose using a D800 or D850 Nikon DSLR.

Issues that may affect the material condition of a monument include disturbance of the ground surface, burrowing animals and encroachment of certain types of vegetation. There is thus a minimum requirement to be able to identify such features with confidence from aerial imagery (Figure 6). The 3–4 m GSD PlanetScope data are not suitable given the types of features that must be clearly visible for this purpose. Assessment of SkySat imagery indicated that it provided adequate generalised views of vegetation cover, which can be a good proxy for condition, and proved sometimes capable of indicating discrete areas of bare earth, for example down to ~2 m across, which may also indicate potential disturbance. In this way, SkySat provided an overview of the monuments concerned, in which gross damage or change in vegetation cover could be detected even if the exact nature of those issues could not be established from the imagery alone. However, for factors such as discrete areas of rabbit burrowing, which have a material impact on a monument, the SkySat imagery does not have the resolution required. This is illustrated with reference to Barnweill, a medieval moated site which survives as an earthwork in long-established grassland (HES, 2022) and is the most visible of the

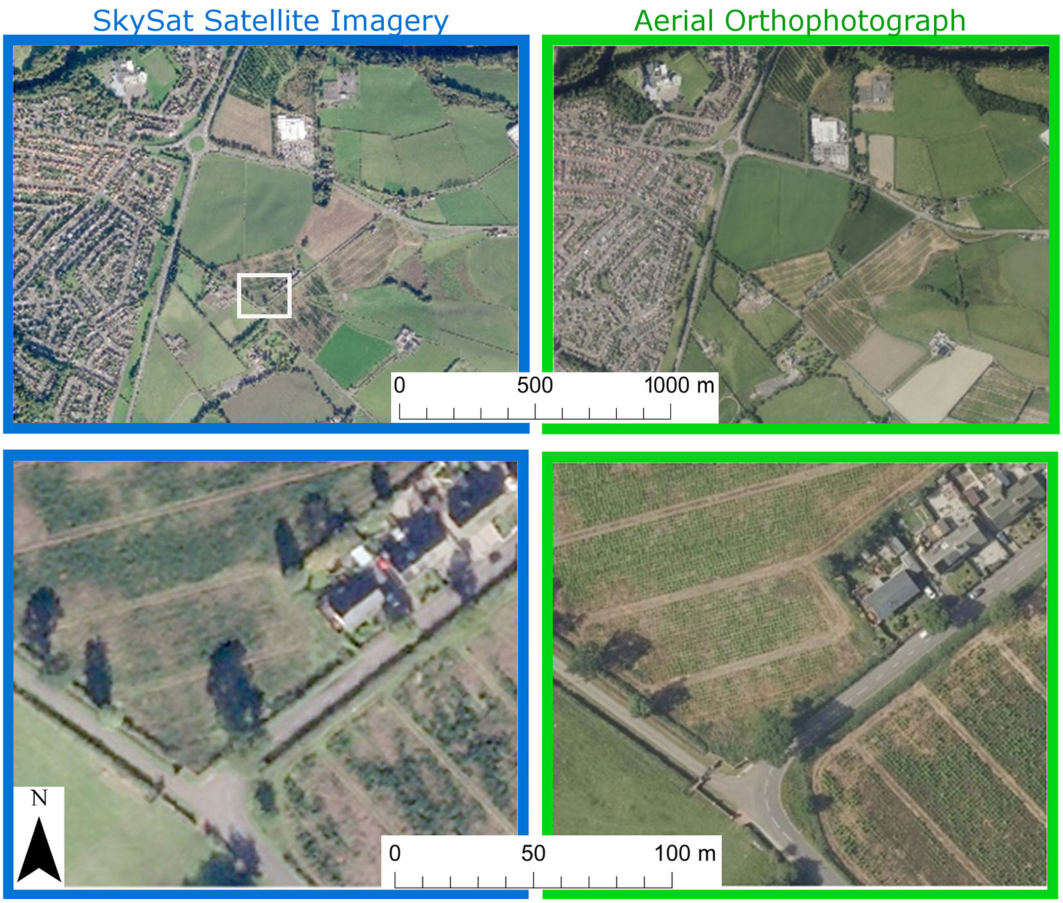

FIGURE 5 Comparison of SkySat imagery (left, Oct 2020) and 0.25 m ground sampling distance (GSD) aerial orthophotograph (right, June–Sept 2019) for an area west of Ayr (AOI 8; Lat: 55.45°, Lon: −4.59°). Note that these images are not co-temporal. Inspection demonstrates that they are directly comparable when viewed at a scale of 1:10 000 (top). At a viewing scale of about 1:1000 (bottom), the differences between the imagery are evident, with the added detail visible in the aerial orthophotograph (right) crucial to identifying land-use with confidence. *Source*: SkySat (left): © Planet Labs Inc. 2020; Orthophotograph (right): © Bluesky International Limited & Getmapping Plc. (2019)

10 scheduled monuments in the Ayr AOI 10 assessed for this project. The comparison of the SkySat image with a 0.25 m GSD aerial orthophotograph and a ~0.15 m GSD oblique aerial image (Figure 6) makes the point that the matters of detail such as damage to surface vegetation are readily seen in the highest resolution aerial photograph, are hinted at in the lower resolution aerial orthophotographs but are not detectable at all in the SkySat image.

4.3 | Detection of archaeological monuments

Ongoing programmes of archaeological survey are a key element of HES's remit to identify, record, understand and interpret the historic environment (Historic Environment Scotland Act, 2014). Routinely, survey increases the number of known monuments in an area by up to 200% (Banaszek et al., 2018, 1–2; Cowley et al., 2020), indicating that there are 10 000 s of presently unknown archaeological sites and landscapes that are not on record and so are vulnerable to destruction. The risks to such remains increase during periods of land-use change, such as are expected in response to climate change, so the current need for such survey work is pressing. While in an ideal world archaeological survey is informed by all readily available data, there is also a need to assess the cost/benefit of that position, especially where extensive (i.e., national) coverage is a key objective and risks such as land-use change are accelerating. Here, there is a need to assess the cost/benefit and fitness for purpose of data (Cowley et al., 2020, 113–6; see also Oltean & Hanson, 2013, for such an assessment in Romania), a position that is as applicable to the assessment of satellite data as it is to, for example, historic aerial photographs (e.g., Cowley et al., 2013, 25–6; Cowley & Stichelbaut, 2012, 228–30).

There are two elements to the assessment of imagery for detection of archaeological sites and landscape—first, the potential to identify earthworks (remains in the surface relief) and vegetation proxies for buried sites, and second, to inform identification of the most productive conditions for the deployment of fixed wing aircraft and other airborne platforms for detailed survey. An underlying concern is the inherent bias of observer-directed aerial survey (e.g., Palmer, 2005)

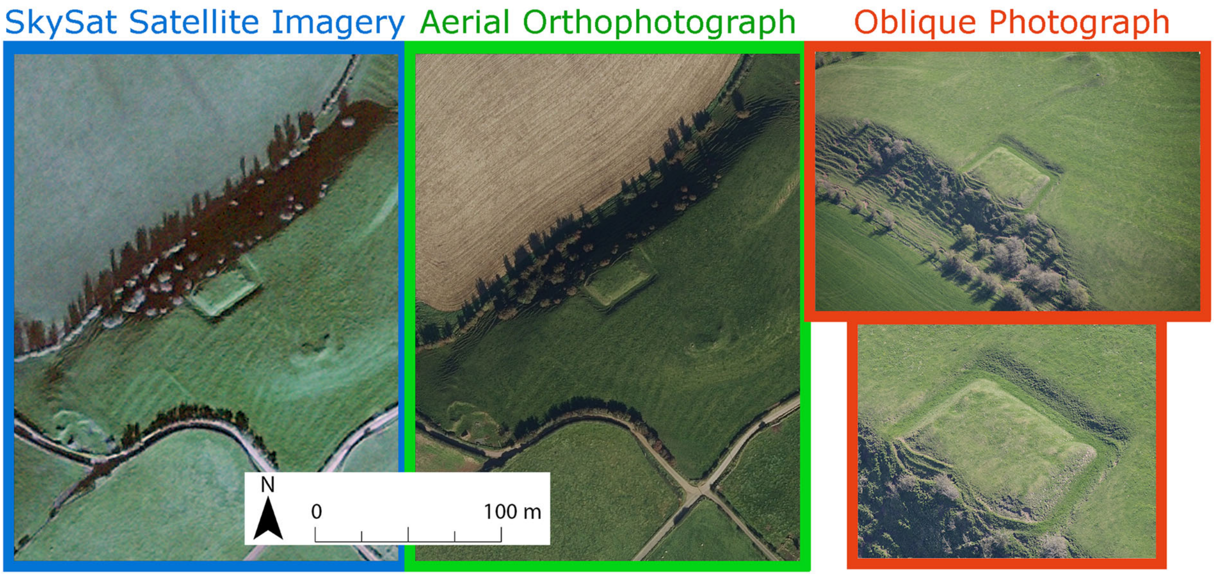

FIGURE 6 Comparison of SkySat imagery (left, Oct 2020), 0.25 m ground sampling distance (GSD) aerial orthophotograph (centre, Sept 2019) and ~0.15 m GSD oblique photograph (right, Apr 2015) for Barnweill showing the full frame (top) and an enlargement (below) (AOI 6; Lat: 55.53°, Lon: −4.52°). Note that these images are not co-temporal. The earthworks of the medieval ditched enclosure are typical of many sites that may require regular monitoring to assess their condition. The SkySat imagery is adequate to detect gross issues, but for many of the routine factors that may impact on condition, 0.25 m GSD imagery is necessary, with the ~0.15 m GSD oblique aerial imagery the benchmark source. *Source*: SkySat (left): © Planet Labs Inc. 2020; Orthophotograph (centre): © Bluesky International Limited & Getmapping Plc. (2019); Oblique photo (right): DP213288 © Crown copyright HES

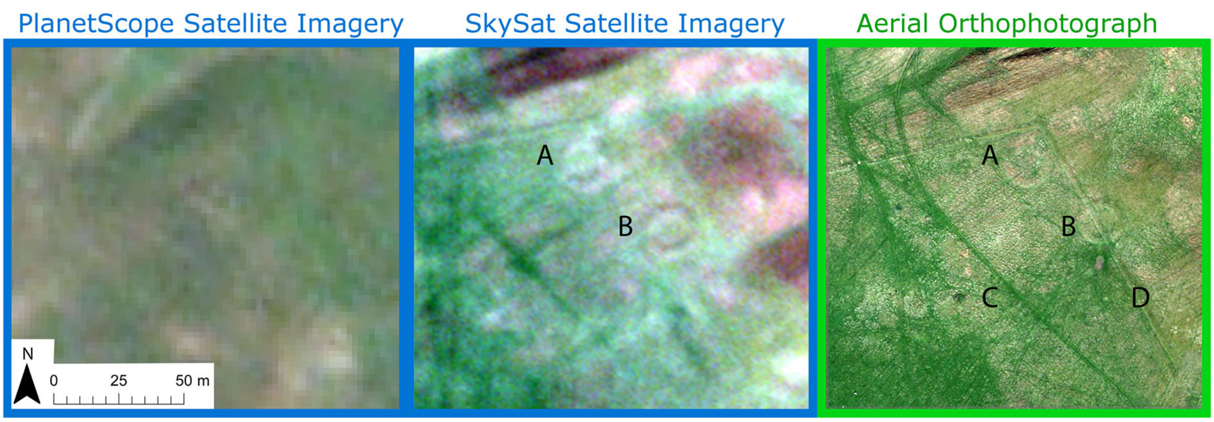

FIGURE 7 PlanetScope (left, Aug 2018), SkySat (centre, Apr 2020) and 0.25 m ground sampling distance (GSD) aerial orthophotograph (right, Apr–May 2020) for a small area in the Borders (AOI 10; Lat: 55.41°, Lon: −2.38°). Note that these images are not co-temporal. For most archaeological remains that occur in Scotland, the 3–4 m GSD PlanetScope imagery is unsuitable for discovery or documentation. In the right conditions, SkySat imagery will record features, including the banks of two post-medieval sheepfolds each measuring about 20 m across (A & B), but detail is lacking. The importance of that detail is illustrated by the 0.25 m GSD aerial orthophotograph, which not only adds certainty to the identifications but also allows the sequence of over-lying rig and furrow cultivation (e.g., C) and field boundary (D) to be observed. *Source*: PlanetScope (left) and SkySat (centre): © Planet Labs Inc. 2020; Orthophotograph (right): © Bluesky International Limited & Getmapping Plc. (2019)

and a recognition that block coverage (i.e., large area) imagery is desirable to mitigate such biases.

In considering the suitability of the PlanetScope and SkySat data for the identification of archaeological sites and monuments, the anticipated character and scale of remains and features, the capacity to acquire imagery during specified periods and the timely availability of imagery are critical. Visibility is determined by the overall size of both monuments and their component parts, and whereas individual monuments may measure over 100 m across, their component parts (i.e., ditches/ramparts) may be less than 3 m across. This means that many anticipated archaeological features will rarely be visible in the 3–4 m GSD PlanetScope data (e.g., Figure 7).

Whereas the identification of earthworks as relief features in imagery will depend on factors such as lighting and vegetation conditions (e.g., Figure 7), for buried archaeological features recorded through vegetation proxies (or cropmarking), the period of data acquisition is time critical. Cropmarking depends on seasonal weather conditions and the state of development in crops (Evans & Jones, 1977; Wilson, 2000), which can vary greatly from year to year and locally or regionally (e.g., Agapiou et al., 2013; Cowley, 2016, 63–5). The relatively narrow window of time for detecting archaeological cropmarking in Scotland spans very late June and all of July, occasionally extending into early August. Current practice relies on observer-directed reconnaissance in a light aircraft operating at an altitude of between 600 and 750 m, informed by generalised weekly soil moisture deficits that provide an indication of dry areas where crops may be stressed. The many sources of bias in this approach (e.g., Cowley, 2003; Oakey, 2005; Palmer, 2005) are recognised as a key driver behind the assessment of block coverage source data, such as SkySat.

For cropmarking, the resolution of imagery is a crucial factor, and because many of the component parts of archaeological features commonly recorded in Scotland as cropmarking are ≤2 m, the SkySat data are on the cusp of reliably resolving such features (Figure 8). Looking beyond simple identification of monuments, or potential objects of interest, the SkySat data lack the definition to allow confident classification. In addition, the extent of cloud cover (Section 3; Figure 3) was an unanticipated issue—or certainly unexpected in the degree to which it comprehensively impacted the availability of imagery during the specified period. Additionally, the timing of the trial reported occurred when the conditions for cropmark formation were poor, though this also reflects the real-world situation in a part of the world with inherently unsettled weather patterns.

However, for assessment of general crop conditions to inform deployment of a fixed wing or other imaging platform, the PlanetScope imagery captured the general extent of crop development/variegation adequately (Figure 4). Whereas soil moisture deficit figures can be acquired from other sources, such as the UK Met Office and from Sentinel data, the major advantage of the PlanetScope imagery is that it shows the state of crops and the degree of variegation directly. This could be a significant potential improvement on current capacity to plan a programme of reconnaissance across cropmark areas, which is informed by weekly generalised soil moisture deficit figures. PlanetScope has a swath width of 25 km, which is a broad enough view of a given landscape to make subjective assessments of local and regional variations in crop conditions. However, such data would need to be available on a weekly, or at the very most bi-weekly, basis as crop conditions can change dramatically in a changeable

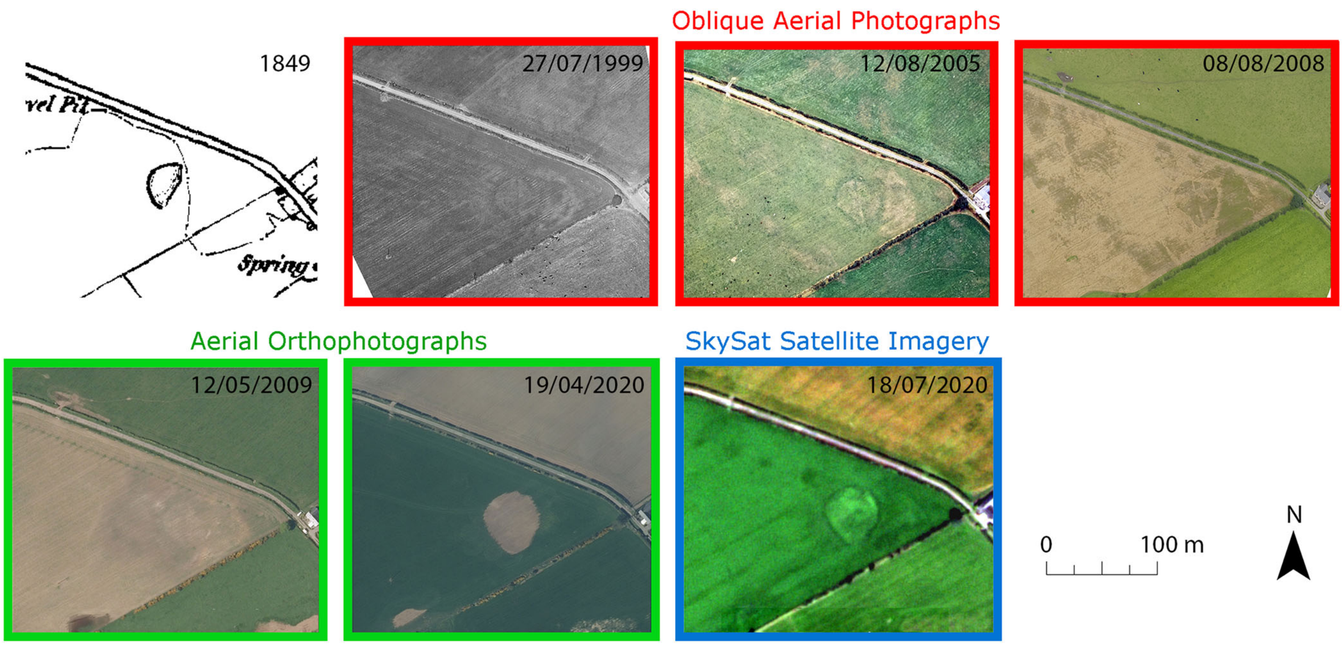

FIGURE 8 While crop variegation was limited during the period of the present study, one previously documented site of an infilled 19th century quarry (top left = 19th century map) was evident at Garthleary near Stranraer (AOI 10; Lat: 54.92°, Lon: −4.97°). The 'time-series' images illustrate the importance for interpretation of complementary views, with variable vegetation responses evident across the ~0.10–0.15 m ground sampling distance (GSD) images from observer-directed survey in 1999, 2005 and 2008 (top). Aerial orthophotographs from 2009 and 2020 (bottom) provide additional views, including ongoing work to fill in the quarry (19/04/2020), but were not captured at an optimal period for recording cropmarking. The SkySat image (bottom right) demonstrates the potential to document large features through crop proxies though the lack of clarity (e.g., the varying sharpness of the edge of the quarry) is a limitation on confidence of interpretation and may be actively misleading. *Source*: Oblique photographs (top row): SC1754605, SC1754644 and DP045538 © Crown copyright HES; rthophotographs (bottom left & centre): © Bluesky International Limited & Getmapping Plc. (2009 & 2020); SkySat (bottom right): © Planet Labs Inc. (2020)

climate like that prevailing in Scotland. The assessment of data availability in Section 3.1 indicates that the PlanetScope data could not be relied on in this regard, in contrast to the other sources of information on potential crop stress, which are not compromised by cloud cover.

4.4 | Summary of data suitability assessment

Table 6 provides a qualitative summary of the image types assessed and their suitability for the stated objectives of the present study. This demonstrates the degree to which archaeological survey and heritage management are dependent on data sources that are not necessarily optimal for the intended purpose. Such reliance on available, but perhaps suboptimal, data and methods is a recurrent issue in archaeological remote sensing (see Cowley et al., 2021). Nevertheless, the present study has sought to foreground the purpose at hand, assessing the suitability of data against that standard. This approach shows the extent to which established methods of exploring landscapes and imaging sites, while suffering from observer bias and suboptimal data, remain viable. This provides a context for the range of source data to be assessed and assimilated in workflows on the basis of suitability for purpose rather than simple availability.

5 | DISCUSSION

The assessment of two commercially available satellite data products reported on here has foregrounded considerations of the purposes at hand, focusing on the relationships between survey objectives and the character of the data. Thus, for example, the form of archaeological sites and the scale of their constituent parts are crucial factors that relate directly to the degree to which imagery has the capacity to resolve them. In structuring our study in this manner, we have aimed to present a 'real-world' assessment of the utility of such data products, the key aspects of which are summarised in the following sections.

5.1 | Data characteristics and suitability

One key theme to emerge from our study, which is unsurprising, but worth stating, is that resolution (i.e., GSD) really matters, especially in parts of the world where archaeological sites and their constituent parts are small. For work that ultimately depends on crisp detail to reveal and classify archaeological sites or monitor condition, the SkySat imagery is just on the cusp of usability, with any degradation towards off-nadir positions or due to atmospheric conditions dramatically lessening its utility. This is a challenge for archaeologists to consider the extent to which the detail visible in 0.10/0.25 m GSD aerial photographs is relied upon, and the need to ensure adequate records for future analysis of features which may only appear fleetingly as crop proxies. Thus, if detail and resolution down to a guaranteed 0.5 m GSD, or better, and crispness of image across a view is the ultimate requirement, the SkySat data fall just short of reliably providing this. We note a slight improvement in sample imagery from late 2020, attributed by Planet to improved processing and the lowered orbit height. This, we believe, will enhance the value of the data for cultural heritage applications but still note the limitations in resolution.

We also note that the lack of consistency in spatial resolution between satellite images, the unclear expression of precise GSD for each image and a lack of transparency with regards to processing techniques are a concern for interpreters. The Planet documentation for SkySat states variations of GSD according to instrument, altitude and data (panchromatic/multispectral) in a framework of 'Ground Resolution after Super-Resolution processing' (Planet, 2021). For SkySat, the outputs are delivered as 0.5 m pixel re-interpolated grid as a result of the data postprocessing, irrespective of the original GSD. This raises the issue of 'granularity' of data, which is important to certain

TABLE 6 A summary qualitative assessment of the varying suitability of different forms of imagery for specified purposes, expressed with 'traffic-light' coding to indicate a range from highly suitable (green) to unsuitable (red)

Imagery type	GSD	Landscape character and change detection	Condition monitoring	Site detection and interpretation
Oblique aerial photographs	~0.10 m	• Limited field of view • Observer bias	• Good detail • Timing can be optimised	• Ideal for interpretation • Timing can be optimised • Inherent observer bias
Aerial orthophotos	0.25 m	• Landscape perspective • Adequate detail	• Landscape perspective • Detail can be lacking	• Landscape perspective • Detail can be lacking • Optimal timing of acquisition unlikely
SkySat	0.75–0.81 m	• Landscape perspective • Adequate detail • Synchronous large area imaging challenging	• Lacks detail for interpretation • Timing of acquisition can be difficult	• Resolution inadequate for all but largest monuments
PlanetScope	3–4 m	• Landscape perspective • Lack of detail may be a challenge	• Lacks necessary detail	• Resolution inadequate

Abbreviation: GSD, ground sampling distance.

applications. Here, a lack of absolute clarity about what postprocessing has been undertaken, what interpolation may have been applied to upscale or downscale the 'original' data and what different expressions of spatial resolution mean is unhelpful and may create inaccurate impressions of higher quality imagery with no real change to GSD. This is an issue for archaeological remote sensing, where a lack of common understandings of how spatial resolution may be expressed is a recurrent problem (e.g., Verhoeven, 2018).

For the broad-brush mapping activities considered, the SkySat imagery, and to a lesser degree PlanetScope, is entirely fit for purpose in both landscape characterisation and assessment of conditions for deployment of traditional aerial reconnaissance. Generally, land-use can be discerned from visual inspection alone, with vegetation indices, for example, adding considerable value to analytical workflows. The timely availability of data to inform planning may, however, be an issue.

For characterisation survey and imaging where detail is not paramount, the SkySat imagery is entirely fit for purpose, though the relatively small tile sizes require well-designed data management procedures. The PlanetScope imagery would be valuable for assessment of crop conditions but would need to be available on a bi-weekly basis at least and is compromised by cloud cover so cannot be seen as a panacea.

5.2 | Data availability assessment

Our data availability assessment has highlighted the significant impact of cloud cover in Scotland on the number and temporal frequency of suitable images from both archival and tasked data sets. This is particularly challenging in the case of high-resolution SkySat acquisitions, which cover comparatively small areas in a single pass. This unreliability caused by cloud is a common challenge for all visual satellite imagers and impacts the suitability of such data for tasked applications that require high temporal frequency, high-resolution imagery to be acquired. This presents a major challenge to designing survey strategies for time critical imaging that do not suffer from the inherent observer bias that traditional fixed wing aerial reconnaissance does.

The assessment of availability of archival imagery highlights an issue that will impact more directly on archaeological and some heritage applications than for some other disciplines. Essentially, the availability of archival imagery, and most especially higher resolution data, depends on tasking patterns, and these will tend not to occur in rural areas that may be of most interest to archaeologists, more often targeting urban areas, or areas of economic or other strategic interest. Historic 'patterns of discard' have a major impact on the availability of aerial photographs and satellite imagery spanning the second half of the 20th century (see Cowley et al., 2010, 3–4), and so too will patterns of tasking and retention on availability of data such as from the Planet constellations now and in the future. Thus, while imaging of the Earth's surface is increasing rapidly, this will not simply ensure that all parts of the surface are imaged at useful times or that the imagery is retained.

5.3 | Working practices

The assimilation of emergent data sources and the working practices that may come with them can be a challenge. We have identified that familiarity with established data sources, such as ≤0.25 m GSD aerial photographs, can mean that the reduced clarity of view undermines the confidence of interpreters. However, while we recognise that is, to a degree, a matter of training, there are also real limitations in applicability of data. The GSD of imagery is one factor influencing usability, relating directly to the scale of archaeological sites and features in Scotland (and areas with similar archaeology). Atmospheric conditions such as haze are a routine problem in a landmass on the edge of a large ocean affecting all forms of imaging but are especially acute with satellite imagery. Such impacts are exacerbated in off-nadir views. Diminishing image clarity reduces the confidence of interpreters in their observations and is a challenge to working with ≥∼0.5 m GSD data, as imagery analysts rely on added detail where there is ambiguity. Taking this work forward will require assessment of the developing needs for imagery, the extent to which such needs can be met by existing solutions such as traditional aerial orthophotography, the role of image processing and the balance between effective imagery and cost implications.

It is also worth noting that HES accesses aerial orthophotographs through a Public Sector Geospatial Agreement (PSGA) and so is tied into an administrative framework for delivery even if the timing of acquisition of these images is not optimised for archaeological and heritage management needs. This means that the significant costs of alternatives may in practice be unaffordable. The HES aerial reconnaissance budget is also small, amounting to about 33,000 GBP per annum, a figure that does not purchase much satellite data. These administrative and budgetary aspects of working practice are a major factor in maintaining a status quo, until such time as the consensus within the Public Sector Geospatial Agreement moves to satellite based solutions. And that consensus may be some way off, as the interest in detailed images, identified here as key for archaeology and heritage management, is also likely to apply amongst other users.

6 | CONCLUSIONS AND FUTURE PRESPECTIVES

Examination of currently available satellite imagery has revealed significant challenges in application to use cases in Scotland, despite the very high resolution and temporal frequency of coverage available from the PlanetScope and SkySat constellations. First, the difference in detail between ∼0.75 m GSD satellite images and 0.25 m GSD aerial orthophotographs is significant, preventing the accurate identification of features such as trees, burrows and discrete archaeological features revealed as crop proxies, as well as reducing confidence in broad-brush land-use classification. Lighting conditions and off-nadir distortion further increase these issues. Commercial companies can provide ∼0.3 m GSD imagery now for civil applications (e.g., MAXAR with Worldview 3 and shortly the Worldview Legion constellation;

Airbus with the Pléiades Neo constellation), and Planet are aiming to expand their constellations to provide high-revisit ~0.3 m GSD data in the near future. However, optical limitations and atmospheric turbulence mean that GSD cannot be expected to improve significantly beyond this in the coming years without a change in mission design and operations, such as making use of very low Earth orbits (Crisp et al., 2021). Satellite data products at ~15 cm resolution are emerging on the commercial market, but these are obtained through post-processing techniques and their suitability for the cultural heritage needs outlined remains unknown.

Cloud cover in Scotland has also been shown to have a major impact on image availability. While increased satellite coverage would increase the likelihood of obtaining cloud free images, the fact that Scotland lies under heavy cloud for ~65% of the summer months means that even with continuous coverage, it will never be possible to guarantee visual imagery vital for time-critical applications. Thus, while current practice in cropmark reconnaissance using a light aircraft suffers from considerable observer bias, it also allows significant flexibility in operating under cloud. Given the requirement for resolution discussed above, the clarity and resolution of Synthetic Aperture Radar (which can penetrate cloud) is not currently adequate for the purposes assessed in this study. It is also worth noting that future availability of imagery will be heavily dependent on patterns of tasking and archiving. These are driven by commercial imperatives that may have little in common with the present or future needs of archaeologists and heritage managers. To these issues can be added the extent to which changing climate will impact on factors such as cloud cover and agricultural practice, which are material considerations for the use cases discussed above. While such impacts are unknown, it is a reminder that the utility of Earth Observation for archaeological and heritage management purposes is very dependent on intertwined complex factors that include weather and modern agriculture.

By assessing commercial satellite data for archaeological and heritage management purposes in a real-world setting, we have identified its potential for cultural heritage purposes in Scotland and similar areas of the Earth, while also noting its limitations. This study suggests that heavy reliance on satellite imagery in Scotland and similar regions would, in fact, restrict the ability of archaeologists to make consistent and reliable judgements. On the other hand, by foregrounding the cultural heritage data needs, satellite data can provide a valuable complementary data source to enhance current methods and fill gaps in existing data sources—assuming it becomes affordable and readily available as the commercial satellite data industry continues to rapidly develop.

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CONFLICT OF INTEREST

No conflicts of interest identified.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Ciara N. McGrath https://orcid.org/0000-0002-7540-7476
David C. Cowley https://orcid.org/0000-0001-8197-260X

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