GUIDANCE NOTE

Earth observation and aerial surveys

Global

6th edition, September 2021

RICS®

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- CICES
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- Historic England
- Remote Sensing and Photogrammetry Society (RSPSoc)
- The Survey Association (TSA).

Contents

RICS professional standards and guidance

RICS guidance notes

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Publications status

Type of document	Definition
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International standard	High-level standard developed in collaboration with other relevant bodies.
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RICS guidance note (GN)	A document that provides users with recommendations or an approach for accepted good practice as followed by competent and conscientious practitioners.
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Key terminology

The following key terms are commonly used in the Earth observation and aerial imagery sector. A full glossary can be found in **Appendix C**.

Accuracy (spatial measurement)	Accuracy of a survey measurement used to quantify the possible difference between an actual dimension, size, relative position or location and the measurement value (**BS 5606**). See **Appendix C** for entries on absolute and relative accuracy.
Aerial photography	Photographs taken from an aerial vantage point.
Earth observation	The process of capturing data about the Earth's physical, chemical and biological systems using remote sensing technologies including surveying techniques, and the collection, analysis and presentation of this data.
Ground-sampled distance (GSD)	The distance between the centres of two consecutive pixels on the ground. GSD is a common way to define and refer to the spatial resolution of Earth observation and aerial imagery.
Hyperspectral imagery	An imaging technique operating across the visible and non-visible parts of the electromagnetic spectrum, typically recording reflected and emitted electromagnetic radiation in very narrow bands.
Interferometric synthetic aperture radar (InSAR)	The measurement of the differences in the phases of the waves between two SAR images acquired over the same area at different times.
Light detection and ranging (LiDAR)	A remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth.
Multispectral imagery	Imagery captured using sensors operating outside the visible part of the electromagnetic spectrum.
Spatial measurement accuracy	The accuracy of a survey measurement used to quantify the possible difference between an actual dimension, size, relative position or location and the measurement value.

Synthetic aperture radar (SAR)	An active microwave remote sensing technology that measures the phase difference between a radar wave emitted from an antenna attached to a satellite or an aircraft and its received echo from the terrain to generate high-resolution images of the surface.
Thermal imagery	Imagery created from detecting and recording the infrared part of the electromagnetic spectrum.

1 Introduction

Earth observation and aerial surveys are used to capture, store and process reflected and emitted radiation from the Earth's surface. The techniques employed include aerial photography, light detection and ranging (LiDAR), and hyperspectral, multispectral, thermal and synthetic aperture radar (SAR) imaging systems. Survey instruments are typically carried by satellites, fixed-wing aircraft, helicopters and, increasingly, by unmanned aerial vehicles (UAVs).

Earth observation and aerial survey data are used to help understand climate change, develop smart cities and contribute to the development of digital twins, improving the efficiency of the construction industry and infrastructure sector. Specific applications include:

- national mapping
- cadastral mapping
- design and construction of transportation infrastructure
- engineering asset management
- land cover classification
- flood zone mapping
- erosion measurement
- riverine and shallow-water bathymetric modelling
- navigation
- 3D city modelling
- heritage recording and
- archaeological landscape analysis.

Organisations are looking to the power of geospatial data to provide insight into our natural and built environments. This will enable improved management of these resources, which will in turn contribute towards a more sustainable future.

1.1 Scope

This guidance note is intended for use by land, sea, engineering and environmental professionals who are acting in an advisory capacity, and by survey-knowledgeable clients who specify their own surveys. It is also intended to be used by Earth observation and aerial survey specialists.

It will help clients communicate their goals, and what they expect to receive in terms of:

- types of data
- accuracy
- resolution
- survey detail and

- final deliverables.

It will help both parties clarify issues such as project constraints and timescales.

This guidance note supersedes *Vertical aerial photography and digital imagery*, RICS guidance note, and contains new sections on LiDAR (topographic and bathymetric) and hyperspectral, multispectral, thermal and radar imaging systems.

The following topics are covered in this guidance note:

- chapters 2–3: pre-project considerations, including the different data capture platforms available and planning requirements
- chapters 4–7: the techniques of aerial photography, LiDAR, sensing in the non-visible part of the electromagnetic spectrum and Earth observation and
- chapter 8: future developments in Earth observation and aerial survey techniques.

This guidance note also contains sample specifications, an accuracy and resolution table that combines information about each technique and an expanded glossary in the appendices.

1.2 Effective date

This guidance note is effective from 4 January 2022.

2 Data capture platform

2.1 Data type

The starting point when commissioning Earth observation or aerial survey data is to consider what the data will be used for. In many cases, this will be self-evident; for example:

- national mapping
- heritage recording
- forestry
- land classification
- rail transportation
- precision agriculture or
- archaeological landscape analysis.

The use case for the aerial survey will determine the type of data that will be most appropriate.

- Aerial photography is the most common type of data as it aligns most closely with the client's view of reality, with features such as trees and buildings instantly recognisable, albeit from a different perspective. The science of photogrammetry was built around the use of stereo aerial photography, from which precise measurements can be made, increasing the utility of aerial photography as an aerial survey technique. Today, dense image matching photogrammetric techniques are used to provide elevation and 3D models including using photography captured from UAV platforms. Most modern sensor systems have the capability to collect four-band red, green and blue (RGB) and near-infrared (NIR) imagery.
- LiDAR is a good source of height information and has found numerous applications in modelling the built and natural environments, including the depth of shallow water in coastal and riverine areas and forest canopy detail.
- Multispectral, hyperspectral and thermal data, sensing outside the visible part of the electromagnetic spectrum, are particularly useful in detecting the health of different plant species.
- SAR data is captured using an active microwave sensor, creating high-resolution imagery of the Earth's surface independently of the availability of daylight or bad visibility due to weather.

Frequently, more than one data type is commissioned for a particular use case. For example, aerial photography and LiDAR are frequently commissioned together, with the photography providing a view of reality and the LiDAR data the third dimension.

Another common combination is aerial photography and hyperspectral imagery, with the latter used to accurately determine plant species.

2.2 Accuracy and resolution

The accuracy of an aerial survey is traditionally expressed by specifying an absolute root mean square error (RMSE) for the positioning of the survey data relative to ground control. Ground control points (GCPs) should be used as an independent check on the mapping accuracy (see **section 3.4**).

The spatial resolution of aerial photography and multispectral, thermal and hyperspectral imagery is expressed as a ground-sampled distance (GSD). The resolution of a LiDAR survey is expressed as the number of points recorded per square metre on the ground, or points per square metre (ppm^2).

Higher-resolution imagery enables more detail to be observed within the scene and thus finer detail to be mapped. GSD is not synonymous with accuracy.

It is important to specify realistic accuracy and resolution requirements that are appropriate for the use case of the aerial survey. This can directly influence the cost of a project. To achieve both a highly accurate and high-resolution dataset:

- specialist (and therefore more expensive) sensors and workflows should be employed
- data should be captured at as low an altitude as possible, which increases the number of flight lines, time in the air and therefore cost and
- a coordinated ground control survey is required, further increasing costs.

Over-specifying or under-specifying a survey can bring about undue cost. For instance, there would be little advantage in specifying high accuracies for a land cover classification of a river catchment area while a survey of the same area for flood zone mapping may demand a higher accuracy.

Appendix B contains a combined accuracy and resolution table for each data capture platform.

2.3 Area of interest

The area of interest (AOI) will influence the choice of data capture platform. The basic premise is that large project areas are captured more efficiently at higher altitudes and at higher data capture speeds.

- Satellite-based sensors are best for capturing areas of hundreds of thousands of square kilometres.
- Manned fixed-wing aircraft can efficiently capture projects in the thousands to tens of thousands of square kilometres, depending on accuracy and resolution requirements. They can carry larger and more complex instrumentation, such as a large-format camera, LiDAR systems and a gyro-stabilised mount, so they can therefore achieve better system accuracy and resolution relative to the flight altitude.
- Manned helicopters can fly lower and slower, are much more manoeuvrable than fixed-wing aircraft and are more efficient at capturing aerial survey data along corridors such as roads, rivers, or railway lines. The lower altitudes at which they can fly enable them to capture higher-resolution and potentially more accurate data, even considering the limitations of their payloads.

- UAVs that are part of an unmanned aerial system (UAS) can carry various aerial sensors and are suited to sites of a relatively small extent in the tens of square kilometres. The recent miniaturisation of LiDAR instruments and cameras has enabled very high-resolution surveys in the order of <10mm GSD to be conducted economically over smaller sites owing to the platform's proximity to the ground.

2.4 Selecting a data capture platform

The use case, AOI and data type have the biggest influence on the accuracy, and data capture platform, for an aerial survey. More than one platform and/or data type can be used for different use cases.

Table 1 is an example of matching data types and data capture platforms in eight common use cases. In practice, there are many other successful combinations.

Use case	AOI	Data type	Accuracy	Data capture platform
National mapping	Large	Aerial photography	High	Manned fixed-wing
City modelling	Large	Aerial photography (nadir and oblique)/LiDAR	High	Manned fixed-wing
Heritage recording	Small	Aerial photography	High	UAV, manned helicopter
Forestry	Large	LiDAR	Medium	Manned fixed-wing
Intertidal mapping, near-shore and river	Large	Bathymetric LiDAR	Medium	Manned fixed-wing
Infrastructure, civil engineering	Small/medium	Aerial photography/LiDAR	High	UAV/manned helicopter
Land classification	Large	Multispectral imagery	Low	Satellite
Precision agriculture	Small	Multispectral imagery	High	UAV

Table 1: The relationship between use case, AOI, data type, accuracy, and data capture platform

2.5 Data capture platform restrictions

Each data capture platform has its own restrictions.

Satellites are on fixed, sun-synchronous orbits passing over the equator at the same time every day, which may or may not suit the project's requirements.

Fixed-wing, helicopter and UAV operations are governed by two global bodies: the **International Air Transport Association** (IATA) and the **International Civil Aviation Organization** (ICAO).

The **European Union Aviation Safety Agency** (EASA) governs operations within the EU. Practitioners should consult the national aviation organisations of their individual country for specific operational details.

For example, the **Civil Aviation Authority** (CAA) is the statutory body that oversees and regulates all aspects of civil aviation in the UK. In the UK, flights above 10,000ft require an aircraft with a pressurised cabin or oxygen for the flight crew. Below this altitude, aircraft must comply with restrictions on flight zones set by the CAA, which are more prevalent and restrictive around dense urban areas and sensitive sites such as prisons or airports.

UAV pilots are required to obtain an operational authorisation (OA). This authorisation is compiled using a risk-based approach according to what the operator wants to do, how it will be achieved and what UAV technology will be used. Using this information, the operator will then have to demonstrate that it can be achieved safely by providing a risk assessment and safety case.

There are three operating categories: open, specific and certified. **CAP 722: Unmanned Aircraft System Operations in UK Airspace – Guidance 2020** provides further details.

UAV operators are also obliged to write an operations manual that must be approved by the CAA. Under standard permissions from the CAA, UAVs are restricted to operating outside controlled airspace – unless they obtain permission from the relevant authority – and have to maintain:

- a distance of 50m horizontally from any assemblies of people (gatherings where persons are unable to move away due to the density of the people present)
- a visual line of sight at all times and
- a maximum height of 400ft above ground level (AGL).

In congested, restricted, or sensitive areas, UAV pilots need to have their operational safety case approved by the CAA and possibly third parties with a legitimate interest in the activity of the flight.

For example, within a flight-restricted zone (FRZ) at a UK aerodrome, further clearances from the aerodrome operator and the air traffic service unit will be required, potentially allowing flights above the standard 400ft AGL limit.

Clients are advised to review the operator's paperwork before commissioning a survey to check the permissions they hold. See **Drones: applications and compliance for surveyors**, RICS insight paper, for more information.

In the EU, EASA registration of UAV operators became mandatory on 1 January 2021. All UAS operators in applicable jurisdictions flying a drone with a weight of more than 250g are required to register, as well as any drone less than 250g that is not a toy and is equipped with a sensor able to capture personal data. The registration number needs to be displayed on the drone. The training requirements and distances to which pilots can operate are set to change significantly, to standardise the legislation across the EU.

3 Project planning

All aerial survey projects have some key items in common regardless of location, extent, data capture platform, type of data, ground control, accuracy or resolution. These items should be addressed systematically during the project planning stage.

In the fast-moving area of UAV surveys, the **International Organization for Standardization** (ISO) has developed standards covering the general specification, product systems and operational procedures.

3.1 Area of interest

The starting point for any survey should always be a geo-referenced digital file supplied by the client showing their AOI. This should be accompanied by a specification document providing details of the target imagery GSD, point density (in the case of LiDAR), accuracy requirements and the deliverable products to be created.

It is prudent to check whether the client's AOI is covered by any suitable existing datasets before commissioning a bespoke survey. There are several aerial data providers that offer licensed data for areas worldwide.

However, the contractor can sometimes simply be supplied with a geo-referenced AOI file and a description of the potential use case for the survey data. An experienced contractor should be able to advise on the specification of the data, the data formats, a schedule of data deliverables and the best sensor to capture the geospatial data to meet the client requirements.

3.2 Project start and end date

Every aerial survey project has a start date and an end date. There are several factors that influence the rate at which an aerial survey project proceeds, including:

- the prevailing weather conditions
- time of year (see **subsection 3.3.3**) and
- the limitations associated with working in congested airspace.

It is important that the client and contractor work closely to define the project start and end dates, taking these factors into consideration. The need for adherence to the contract requirements and a completion date should be tempered by the need to produce an acceptable product.

3.3 Project constraints

The project constraints listed in the following subsections should be identified and addressed at the earliest opportunity.

3.3.1 Military or civil security clearances

These may be required to fly over, photograph or process data of sensitive locations, or to operate in particular countries. In some cases, this may require an in-air observer in a manned aircraft during the data capture. The data captured may also need to be processed in the host country within secure certified facilities.

3.3.2 Air traffic control requirements

Some elements of air traffic control are required to operate fixed-wing aircraft, helicopters and UAVs in congested airspace. Permissions, which are time-sensitive, may need to be applied for in advance. Permissions are more difficult to obtain around major airports or over military training areas.

3.3.3 Time of year

Flying can take place all year round. However, it is recommended to specify that the angle of the sun is at least 15° above the horizon, which, in the northern hemisphere, generally coincides with a flying season between April and October. A sun angle of >15° is high enough to provide optimal lighting conditions; lower sun angles may result in deep shadows, particularly in urban areas or where there are considerable differences in the height of the terrain. Captured at lower altitudes, across smaller areas, UAV surveys tend to be less reliant on sun angle. LiDAR surveys are not dependent on sun angles.

Some clients may also specify that flying should take place during 'leaf-off' conditions – that is, when there is minimal growth on trees – to provide better visibility of the ground beneath. The timing of this period is variable and should be subject to agreement between the client and the contractor.

Choosing the day(s) on which to fly is crucial in determining the quality of the final image. A balance should be found between flying in suboptimal conditions, risking the client rejecting the photography, and waiting too long for better conditions, lengthening the project acquisition period.

3.3.4 Tidal constraints

For coastal projects, tide times may be a significant constraint where it is beneficial for the maximum amount of intertidal area to be exposed during the data capture period. Clients may specify set periods of time before and after low tide during which data can be captured; these are known as the tidal windows.

Where the project specifically includes the capture of shallow seawater depth, the tides may be less of a limitation, except to the extent that fluctuations can have a significant effect on water clarity and scattering. Tide-level monitoring, as well as monitoring of other factors such as wind speed or direction and sea state can be important to the success of bathymetric surveys.

Tide-level monitoring can be effectively achieved using the Vertical Offshore Reference Frames (VORF) model from the UK Hydrographic Office (UKHO) and accessed via the **ADMIRALTY Marine Data Portal**. Worldwide, there are other models such as **VDatum**, published by the US National Oceanic Atmospheric Administration (NOAA), and **Bathyelli**, published by Service hydrographique et océanographique de la Marine (SHOM) in France. In areas where the relationship between the reference ellipsoid and tidal level, or chart datum, is unknown, provision should be made to capture the tidal height alongside other data, so the water depths can be accurately determined in relation to the required vertical datum.

3.3.5 Health and safety/environmental requirements

Health and safety assessments will need to be prepared, for example for low-level flights in sensitive or congested areas, or for flights taking place during unsociable hours.

Modern LiDAR systems include high-powered lasers and as such their use needs to be considered with respect to eye safety. The ISO provides good advice in this area together with **ANSI Z136.1 Safe Use of Lasers** in the US. Alternatively, the LiDAR instrument manufacturers should be able to provide eye-safety details on products.

3.3.6 Special limitations

There may be flying limitations or restrictions relating to observance of religious days or for security reasons.

UAVs tend to operate at lower altitudes and it is advisable to consider the potential for public interest in the flight scheduling. For example, if operating in the vicinity of a school, it is prudent to inform the school of the planned survey and perhaps even schedule the project for outside school hours.

A second example would be flying above or near transportation infrastructure, where the owners or operators will need to be informed in advance of any flight taking place. See **Drones: applications and compliance for surveyors**, RICS insight paper, for more information.

The identification of suitable take-off and landing sites when operating a UAV can be a significant project constraint, particularly on larger projects where multiple sites are required. This should be addressed at an early stage. It may mean arranging access to private land or securing permissions to use publicly accessible land to ensure that the necessary clearance distances are met.

3.4 Ground control requirements

Independent GCPs are required to support the data processing and verify the accuracy of the final product. If onboard survey-grade global navigation satellite system (GNSS) and inertial measurement unit (IMU) airborne control is used, there may be no need for full ground control; however, ground verification points should still be established. Verification points are control points that are not used in the data processing process, and set aside to independently verify the accuracy of the final products.

The primary method for determining absolute position within an agreed coordinate system is typically high-precision static GNSS; users should refer to the current edition of **Guidelines for the use of GNSS in land surveying and mapping** RICS guidance note.

To be effective, GCPs should be captured to a standard of accuracy that is of an order significantly higher (three times, for example) than that required by the final product, using a professional land survey technique. Capturing the GCPs to a higher standard of accuracy enables a buffer for additional random error propagation that may occur during the product creation process.

If high relative accuracies are required, a total station and precision levelling technique may be appropriate. This is most commonly the case with UAV surveys on discrete sites, such as in the rail environment.

The GCPs should be specified in the coordinate system for the final imagery product output. The contractor should agree with the client on the number accuracy, location, type and distribution of verification points to be surveyed to provide adequate evidence to support the final accuracy claim. It should be remembered that final accuracy is a function of inherited inaccuracies from GNSS-derived absolute control, and relative inaccuracies inherent in platform and system data capture.

For an airborne LiDAR bathymetry survey, a control area on the seabed may be used. Such an area should be captured using multibeam sonar or dense overlapping single-beam sonar, and be at a site inside the survey area and at depths within the specified range for the survey.

3.4.1 Control points for imagery surveys

For all types of imagery, GCPs can either be pre-marked or captured on points of detail after the flying mission is complete. Pre-marking is essential in areas where there is no hard detail, for example in areas of sandy desert.

The advantage of pre-marked points is that there will be no ambiguity in their position when they are used in the aerial triangulation process. The disadvantage of this approach is that they may have been removed before the flight mission takes place. Pre-marking is the most common approach for UAV surveys, and is highly recommended.

Points of detail may be harder to locate or observed in error within the aerial survey data, but they can be captured in the photography soon after the mission is complete, ensuring that up-to-date points are used.

Imagery surveys captured with sensors that do not include a fully integrated GNSS and IMU component will require full ground control as necessary to achieve the specified product accuracy throughout the survey area. Control points should be evenly spread and located near the extents of the model area. For example, they could be positioned in the overlaps between every five images along the strip for manned aerial surveys, depending on the terrain. Control could then be placed in this manner in every third strip within the block.

For UAV surveys where suitable direct geo-referencing is not available, and where accurate height information is required (on topographic surveys, for example), points could be positioned in the overlaps between every two to three images along the strip. The potential cost of an additional ground survey needs to be balanced against the overall accuracy required on the project, and the surveyor’s need to evidence that accuracy.

With the use of GNSS and IMU data, the amount of ground control can be reduced.

It is good practice to observe two or three points in each ground control location, with one to act as a verification point or as a backup if others become obscured. Each point should be accompanied with a detailed witness and location diagram, including a photograph of the site to aid in the identification of the point on the imagery.

See the current edition of **Guidelines for the use of GNSS in surveying and mapping**, RICS guidance note, for more information.

3.4.2 Control points for LiDAR surveys

For LiDAR surveys, there are two types of control point:

- ground control areas (GCAs), grids of 121 points that provide a representative sample to validate the height of the captured data and
- GCPs, which are captured on points of detail to validate the plan position.

GCAs and GCPs should ideally be captured in the same locality. The number of points required is dependent on the size of the AOI and the flight line configuration. Ideally, they should be no more than 10–15km apart and located under crossing flight lines if possible.

GCAs do not necessarily need to be completely flat; a slope of <10° is acceptable. They should be established on hard, smooth surfaces within the survey area, away from aerial obstructions such as tall buildings or trees. If there is space, a 5m × 5m grid should be established with a point roughly every 0.5m, giving a total of 121 points. If this is not possible, an appropriate shape that captures 121 height points should be chosen. This number will allow some height points to be set aside for height verification purposes.

GCPs should be captured on points of detail – on hard surfaces within the project area, away from overhead obstructions – that can be located within the LiDAR AOI. Suitable points are along the tops of kerbs, road markings and ridges of gabled roof structures; 20 points per location are enough for this purpose, including several verification points.

3.5 Project reports

The contractor should submit a progress report at regular intervals on the acquisition of the data and the production of the derivative products.

This should detail:

- information on each flight
- location
- ground control locations, witness diagrams, ground control network adjustments
- verification of the accuracy of the survey; this is best achieved by observing additional GCPs to act as checkpoints during the verification process (see **section 3.4**) and
- the derivative products produced.

Clients may also request that they are informed of progress at significant milestones, for example, immediately before the commencement of data acquisition, on completion of data acquisition and during the data production and deliverable stages.

The time between the data acquisition and quality acceptance of the derived products by the client should be kept to a minimum, to reduce the risks involved with additional work.

A full survey report should be supplied by the contractor at the completion of the project. The contents of this report should be specified by the client.

3.6 Form of contract

Where the form of contract is not specified by the client, it is recommended that this guidance note is used, along with the project information requirements set out in section 1 of the current edition of **Measured surveys of land, buildings and utilities**, RICS guidance note. **Appendix A**, below, contains sample specifications for aerial photography, LiDAR, thermal and Earth observation data.

3.7 Data ownership and copyright

The client should decide whether they wish to retain the ownership and copyright of the captured data and the derived products. The options for data ownership and copyright are as follows.

- The data and products become the property of the client on completion and final payment of the contract.
- Under an agreement with the client, the contractor has the right to resell the data under a separate agreement for royalty payments.
- The data and products remain the property and copyright of the contractor.

4 Aerial photography

Aerial survey cameras come in two forms:

- frame cameras, where the imagery is captured frame by frame in a traditional sense and
- push-broom scanners (also known as along-track scanners), where the image is built up line by line.

Frame cameras are the most widespread kind used for aerial surveys.

The term 'metric' is used to identify a camera that has been specifically made or modified for photogrammetry. They are factory-calibrated, and the calibration parameters are used to remove distortions in the assembled digital images. This is particularly important during the data processing stages where the successful removal of image distortions will have a positive effect on the subsequent 3D photogrammetric data products.

The use of a metric camera designed for photogrammetric data capture should increase the utility of the data captured. Camera geometric and radiometric calibrations should be periodically validated on the schedule recommended by the manufacturer.

UAVs typically use non-metric cameras, and a structure from motion (SfM) photogrammetric technique to create the data products. It is therefore important that the surveyor is sufficiently competent to correctly calibrate the camera themselves, or is sufficiently knowledgeable about the process of self-calibration that most SfM software packages now use, to avoid adversely affecting the achievable accuracy of the project.

4.1 Key considerations

4.1.1 Footprint area

It is recommended that the camera photosensor – charge-coupled device (CCD) or complementary metal oxide semiconductor (CMOS) – and lens combination be selected to minimise the number of images needed to cover the contract area.

The size of a digital camera's photosensor determines the footprint area covered by a single frame on the ground. All other factors being the same – such as the lens and the flying altitude – the larger the photosensor array is the larger the camera footprint coverage will be, as described in **subsection 4.1.3**.

Some digital frame cameras use multiple photosensors in their construction, and the images from the individual photosensors are 'stitched' together by processing software to form a larger image or footprint on the ground. A larger camera footprint requires fewer images to cover the contract area, improving the efficiency of both the data capture and subsequent data processing.

Medium- or small-format cameras typically have a single photosensor, making them impractical for large survey tasks due to their smaller footprint and therefore the greater number of strips of photography required to be flown for the same area.

4.1.2 Focal length

A typical multi-purpose lens for manned aerial survey will have a focal length between 70mm and 210mm. Shorter focal lengths increase ground footprint and can produce more precise height measurements. Longer focal lengths will improve the GSD of the imagery flown at the same altitude. Longer focal lengths also reduce relief displacement and are advantageous for image capture in urban areas with tall buildings. Longer focal lengths are also advantageous when the project GSD can be achieved at flight altitudes above restricted airspace.

In the case of UAVs, a shorter focal length of between 20mm and 80mm is generally recommended, reflecting the small sensor sizes available to be carried by a drone. Typically, a CMOS sensor on a UAV camera will be between 25mm and 35mm in width and breadth.

However, medium-format sensors are now small and light enough to be carried on a UAV. These sensors with larger focal lengths have greater image footprints at a given GSD – leading to more efficient data capture – and enjoy improved low-light performance due to the use of CMOS focal plane technology.

4.1.3 GSD

The GSD of the imagery is determined by:

- the choice of camera lens focal length
- the pixel dimensions of the sensor array and
- the altitude at which the survey is flown.

The relationship between focal length, GSD, flying height and coverage is explored in Table 2.

Focal length (mm)	120	120	210	210	210
GSD (m)	0.10	0.05	0.05	0.10	0.03
Flying height (m)	3,000	1,500	2,625	5,250	1,500
Cross-track coverage (m)	2,646	1,323	1,323	2,646	756
Along-track coverage (m)	1,700	850	850	1,700	486
Footprint (km²)	4.50	1.12	1.12	4.50	0.37

Table 2: Relationship between focal length, GSD, flying height and coverage for a 4-micron pixel large-format aerial camera

Halving the specified GSD and maintaining the focal length will reduce the flying height and consequently the footprint of a single image by a factor of four. This in turn will increase the number of flight lines and time in the air.

Increasing the focal length will enable the GSD and image coverage to be maintained while flying at a higher height, improving data capture efficiency.

Lenses with long focal lengths are suited for data capture at higher altitudes. Shorter focal lengths will provide wider coverage from the same altitude, but not necessarily an improved GSD.

It is normal for digital imagery output to be quoted as a GSD rather than the traditional photographic scale.

The same principles apply for medium-format aerial cameras with lens focal lengths of 50mm and 80mm, as shown in Table 3.

Focal length (mm)	50	50	80	80	80
GSD (m)	0.10	0.05	0.05	0.10	0.03
Flying height (m)	962	480	769	1,538	480
Cross-track coverage (m)	1,032	515	516	1,032	322
Along-track coverage (m)	775	387	388	775	242
Footprint (km²)	0.80	0.20	0.20	0.80	0.08

Table 3: Relationship between focal length, GSD, flying height and coverage for a 5.2-micron pixel medium-format aerial camera

Table 4 has been prepared with a small-format aerial camera suitable to be carried on a UAV platform with 35mm and 80mm lens options.

Focal length (mm)	35	35	80	80	80
GSD (m)	0.005	0.010	0.010	0.005	0.002
Flying height (m)	35	70	160	80	35
Cross-track coverage (m)	41	83	83	41	18
Along-track coverage (m)	31	62	62	31	14
Footprint (m²)	1,285.06	5,140.22	5,140.22	1,285.06	245.97

Table 4: Relationship between focal length, GSD, flying height and coverage for a 5-micron pixel small-format aerial camera

Note that the footprint coverage is in m^2 for the small-format camera in Table 4.

4.1.4 Restriction of image movement

Restricting the amount of image movement during exposure and keeping the camera as level as possible during random instances of air turbulence can significantly improve the image quality, particularly at large scales. This principle equally applies to imagery captured from manned and UAV platforms.

The image movement is determined by:

- the speed of the aircraft
- the rotational motions of the aircraft during the exposure period
- the camera exposure time and
- the GSD of the imagery.

Image movement should not exceed 25 microns over three or more consecutive exposures. This may require the use of a camera with:

- forward motion compensation (FMC) and
- a gyro-stabilised mount during turbulent conditions.

For cameras using CCD photosensors, FMC is a digital or mechanical compensation technique implemented using time-delayed integration (TDI). For cameras using CMOS photosensors, FMC is implemented electro-mechanically. FMC reduces image movement due to the speed of the aircraft over the ground in the direction of flight.

Gyro-stabilised camera mounts for manned aircraft are designed to reduce camera tilts and sudden rotations along three axes, and are frequently controlled using GNSS and IMU data. Maintaining the camera in a flat and level position for both nadir and oblique photography at less than 2° from the horizontal is desirable. An occasional exposure with up to 4° may be permitted, provided the minimum forward and lateral overlaps are maintained (see **subsection 4.2.2**). Rotation in the vertical z-axis should not exceed 5° as measured between the direction of flight and a line parallel to the image frame.

In the case of a UAV platform, a stabilised mount could be employed to hold the camera as level as possible (less than 2° from the horizontal is desirable) at the time of exposure and reduce the amount of rotation around the z-axis to less than 5°. This is harder to achieve with a fixed-wing UAV platform, or when UAVs are working near their effective operational limits (in high winds, for example).

The contractor should select the equipment necessary to provide the product quality required under the flying conditions at the time of photography.

4.1.5 Directly geo-referencing aerial imagery

Using GNSS coupled with an IMU during the capture of vertical and oblique aerial imagery significantly increases the utility of that imagery. GNSS and IMU systems enable significant savings in the ground control and aerial triangulation effort required to provide accurate positioning of imagery, both for subsequent mapping projects (see **subsection 4.4.6**) and to produce orthophotography (see **subsection 4.4.4**).

These systems usually require access to GNSS base station data, which can either be captured specifically for the project or data that comes from a continuously operating network. However, companies specialising in navigation are now developing precise point positioning (PPP) solutions to remove errors resulting from orbital and atmospheric delays without the need for base stations.

Evidence should be provided by the contractor that the GNSS and associated IMU and camera are tested at regular intervals. This is particularly true where the camera components have been removed and reinstalled on the aerial platform. The misalignment calibration procedure calculates the angular misalignments between the platform and the sensor, which are then applied to the data when producing positioning and exterior orientation files.

The collection and supply of GNSS (and sometimes IMU) data is considered a standard practice. The camera positions can be outputted in the coordinate system of the client’s choice.

4.1.6 Calibration

Calibration can apply equally to aerial cameras employed on manned survey aircraft or for camera units used on UAVs. Sensors should be both geometrically and radiometrically calibrated. Radiometric calibration is particularly important when multiple sensors are used on the same project.

Each camera lens unit to be used on the contract should be calibrated, cleaned, tested and certified by the camera manufacturer or by a calibration centre that is recognised internationally or approved by the camera manufacturer. This should be carried out less than two years before the date of the photography. The two-year period is in recognition of the fact that modern lenses remain stable and that the cost of an annual recalibration in countries without local laboratories may be considered excessive.

The calibration certificate should contain the following information:

- name and address of the calibration centre and name of authorised signatory
- date of calibration
- camera manufacturer's serial number for the lens unit
- calibrated focal length of the lens unit in accordance with the manufacturer's recommendations and
- radial and tangential distortion parameters in microns; grid-based geometric distortion tables are also acceptable, and the measured distortion should fall within the limit defined by the manufacturer for the lens type.

If the contractor becomes aware of anything that may affect the calibration of the camera, the client should be informed immediately.

Digital cameras are calibrated and electronically adjusted by the manufacturer to bring the system to a 'zero' state, or within the manufactured tolerances as stated on the calibration certificate. The calibration data file produced during the calibration process is used in the first stages of image data processing. This data file would not normally be provided to the client unless the supply of raw data is specified as part of the contract.

Non-metric cameras should be calibrated as above where possible. However, camera self-calibration methods do exist, using imagery captured coincidently within the project data. UAV-captured imagery is usually processed using SfM-based software incorporating some elements of self-calibration.

4.2 Flying and coverage

4.2.1 Flight lines

Nadir (near-vertical) photography should be flown in approximately straight and level runs (strips) to achieve full stereoscopic coverage. There is little cost saving to be obtained by reducing the overlaps between exposures to a minimum. Full stereoscopic coverage will maximise opportunities for future use of the data. Clients should check particularly with UAV operators that the imagery they capture can be formed into stereo pairs.

Oblique photography should also be flown in approximately straight and level runs to achieve full coverage of the contract area. Modern aerial camera equipment can capture nadir photography simultaneously with oblique imagery. Commonly, four oblique cameras are employed, two along the flight line and two additional cameras either side, inclined at 45°. Flight planning procedures need to ensure that, where a nadir camera is flown simultaneously with oblique cameras, the resulting coverage is compatible.

If obliques are captured for mapping or for SfM image processing, care should be taken to ensure that their exposure maximises the depth of field and resolution of the imagery.

Contractors commonly prepare flight lines that are aligned either east–west or north–south, unless the client has a specific request for the orientation of the photography, or a more suitable flight line orientation is dictated by:

- the terrain
- air traffic control restrictions
- the avoidance of secure sites or
- the capture of tidal areas.

Coverage of corridor features, for example for transport infrastructure, can be achieved with the use of additional flight lines to capture the bends in the most economical manner.

Oblique projects are also frequently planned either in a north–south or an east–west direction, rather than off grid. This means that every spot has coverage from the north-, south-, east- and west-facing cameras, with the camera direction and compass points being maintained.

Once the minimum number of runs required to cover the target area has been calculated, taking account of the terrain, the spacing between flight lines may be adjusted to increase and equalise the lateral overlap between each run.

There should be no duplicate run/strip or frame numbers. The sequence should be maintained even if the target area is subsequently flown in several missions.

Flight plans may be reused where there is a requirement for an ongoing repeat or monitoring survey.

4.2.2 Overlap

Forward overlap is required to ensure adequate formation of stereoscopic coverage. Lateral overlap (also known as side-lap) is required to ensure that no areas are missed between adjacent flying lines. Specifying the correct amount of side-lap also reduces imagery occlusions due to relief displacement at the format edges and to tie the adjacent strips together.

The forward overlap between successive exposures in each run is usually between 60% and 80%. The side-lap between adjacent strips is normally between 15% and 40% for flying heights greater than 1,500m AGL, increasing to between 20% and 40% for lower flying heights. An allowance of ±5% of the selected overlap is permissible.

The forward overlap is related to the sensor field of view (FOV) – the larger the FOV of the camera system, the larger the occlusion areas. The side-lap should be specified taking the camera FOV into account, and therefore reducing the occlusion areas as much as possible. Sensors with a smaller FOV do not require large amounts of side-lap.

In urban areas with high-rise buildings, a forward overlap of 80% or even 90% and a side-lap of 30% is normally used. By increasing the coverage, each tall building will appear in more frames, thus increasing the choice of images that show the building to appear vertical.

Exceptionally, the side-lap may be increased to 60% (along with a forward overlap of 80%) by clients who intend to use the imagery to produce 3D city models.

Imagery acquired using a UAV and intended for SfM processing will normally require the higher figure of 80% forward overlap and a 60% side-lap, and may benefit from additional oblique imagery.

In coastal areas where a run crosses the shoreline, the forward overlap can be increased to 90%. The increase in overlap should include at least three photo centres over land.

In mountainous areas, where it is impossible to maintain the usual side-lap requirements, short infill runs should be flown, parallel to and between the main runs, to fill the gaps. Where ground heights within the area of overlap vary by more than 10% of the flying height, a reasonable variation in the stated overlaps is permitted, provided the forward overlap does not fall below the selected percentage and the side-lap does not fall below 10%.

In oblique imagery, overlaps are not so crucial because stereo imagery is not expected. However, oblique imagery is still planned with some overlaps to ensure full coverage over the contract area. Extra flight lines may need to be considered to ensure full oblique coverage.

Push-broom imagery sensors acquire multiple strips of images simultaneously (forward, nadir and backward) as opposed to operating via a series of separate exposures. Stereo viewing is derived from the fixed geometry of the sensor. Scanner-based imagery should therefore be flown in a continuous swath, with a minimum of 20% side-lap (25% in areas with large differences in terrain heights and in urban areas).

4.2.3 Acceptable quality limits

The following list is intended to act as a set of acceptable quality limits (AQLs) to provide guidance on the subjective topic of image quality. The prevailing weather and atmospheric conditions, which are outside the control of the contractor, are the most important factors that affect the image quality, and therefore the AQLs. The client and contractor should work closely together to ensure a mutually acceptable result. This guidance note applies equally to nadir imagery and oblique imagery.

- The photography should be taken at any solar altitude above 15°, unless special restrictions are included.
- The imagery should be sharp.
- There should be minimal flare from expanses of glass, water, or cars.
- Colour and light balance should be uniform.
- Contrast should be consistent across the block of imagery.
- There should be a good match between flight runs and adjacent images.
- The photography should only be flown in conditions where the visibility does not significantly impair the image quality and detail is not lost because of rain, atmospheric haze, dust, or any other conditions detrimental to the photographic image.

- The photography should be substantially free of cloud, dense shadow, or smoke. Isolated areas should not be cause for rejection of the photography, provided the intended use is not impaired. Typical tolerances for cloud and cloud shadows may be less than 5% for a single image and 1% over a contiguous block of images.
- The photography should conform to any specific radiometric values specified by the client, including:
  - mean histogram luminosity values
  - mean of the individual colour bands or
  - standard deviation for each colour band.

4.3 Aerial photography accuracy and resolution table

The relationship between aerial photography GSD, flying height and achievable photogrammetric accuracies is well known.

Table 5 is an expanded version of the table quoted in *Vertical aerial photography and digital imagery*, RICS guidance note, including additions for high-altitude fixed-wing aerial photography, photography captured from a helicopter and photography captured from UAVs.

It is worth noting that Table 5 is based on high-end equipment available on the market today and that many factors may affect accuracy and resolution. Therefore, the values quoted can only be referenced as achievable.

The values quoted are RMSE accuracies on hard surfaces covering 90% of the project AOI.

Platform	Height (m)	Height (ft)	Achievable accuracy for plan X, Y (m)	Achievable accuracy for height Z (m)	Resolution – GSD (m)
UAV	30	100	±0.01	±0.015	0.005
UAV	122	400	±0.04	±0.06	0.02
Helicopter	319	1,047	±0.03	±0.04	0.02
Helicopter	638	2,093	±0.06	±0.08	0.04
Fixed-wing	1,200	3,937	±0.06	±0.08	0.04
Fixed-wing	2,250	7,382	±0.11	±0.15	0.08
Fixed-wing	4,500	14,764	±0.23	±0.30	0.15
Fixed-wing	7,500	24,606	±0.38	±0.50	0.25

Table 5: Achievable accuracy and resolution values for vertical aerial photography

The UAV flying altitude of 400ft represents the highest altitude at which a UAV can be operated in the UK without the approval of an operational safety case.

For comparison purposes, Table 5 is based on a camera focal length of 120mm for the fixed-wing aircraft, an 80mm lens on a helicopter-based medium-format camera system and a 35mm UAV camera lens. The miniaturisation of camera technologies has meant that medium-format cameras (with a focal length of around 80mm) are now small and light enough to be carried on UAV platforms.

Table 5 shows that mapping accuracies of 1.5 times the GSD can be achieved horizontally and two times vertically, using a traditional photogrammetric approach including a rigorous aerial triangulation process. These values are a reflection on the quality of the camera and navigation equipment that can currently be carried by each platform.

SfM techniques are popular with UAV data processing workflows, where a rule of thumb for calculating likely achievable relative accuracies is:

Plan = 2 x GSD

Height = 3 x GSD

4.4 Digital imagery deliverables and products

4.4.1 Digital imagery

The contractor may supply all overlapping digital imagery on request, which enables the client to take advantage of any future improvements in image processing techniques.

The client may specify the image format, image compression and data transfer medium. Stereo imagery data can require large volumes of disk space, so clients are likely to specify a format that can be easily incorporated into their archive system.

It is rare that stereo imagery is supplied without the accompanying positional information, derived from a GNSS/IMU navigation system. As a minimum, for each image, this should consist of:

- a unique run and frame number
- date and time of capture (GNSS time)
- easting, northing and height position, and the three photogrammetric camera rotations – omega, phi and kappa – in the client's choice of coordinate system
- imagery GSD and
- camera and aerial platform details.

The accompanying positional information is frequently used to geo-reference the imagery to meet the client's requirements. This can be simply supplied in a text file or database format.

4.4.2 Metadata

The data should be accompanied by metadata that describes the instruments used to capture the data and any processing applied. The following international standards are relevant to documenting metadata for imagery:

- **ISO 19115-1:2014, Geographic information – Metadata – Part 1: Fundamentals**
- **ISO 19115-2:2019, Geographic information – Metadata – Part 2: Extensions for acquisitions and processing** and

- **ISO/TS 19115-3:2016, Geographic information – Metadata – Part 3: XML schema implementation for fundamental concepts**.

Metadata should be made available to client organisations for onward supply to their customers. It may be specified for digital imagery or for any other digital imagery products described in the following subsections.

Metadata standards are normally specified by the client organisation. Positional data derived from a GNSS/IMU navigation system is a good example of metadata.

Other examples of metadata are:

- date and time flown
- GNSS time
- geographic reference frame
- flying height
- coordinate system
- geodetic datum
- resolution
- file size
- camera system
- oblique image orientation and
- date of production.

4.4.3 Stereo imagery

Digital stereo imagery is a raw product used to create more complex geospatial data. This can in turn provide insight into the business proposition for which the imagery was commissioned. For example, supplying imagery with geo-referenced coordinates enables basic plan measurements to be taken and exploited for numerous applications including stereo viewing, elevation extraction and creation of orthophotos.

Aerial photography can be used to form stereoscopic models, which are created using a mathematical model to replicate the geometry of the image at the time it was captured. This produces a precise geographical location for each individual image at the time of exposure. The position of each image is described using three coordinates (easting, northing and height) and three rotations (omega, phi and kappa) around the three principal camera axes.

Aerial triangulation can then be used to enable the viewing of models in 3D. This is a technique in which the imagery is tied together, geo-referenced and verified against independently captured GCPs, within a rigorous least-squares adjustment model. The result is a 3D coordinate for every pixel in the image, enabling 3D measurements to be taken from the imagery.

Computation of refined orientations for each image with rigorous aerial triangulation significantly increases the utility of the imagery. It provides the basis to:

- create orthophotography (see **subsection 4.4.4**)
- generate digital terrain models (DTMs) and digital surface models (DSMs) (see **subsection 4.4.5**)

- extract 3D mapping data (see **subsection 4.4.6**) and
- create additional specialist products such as:
  - 3D building modelling
  - tree mapping and
  - line of sight analysis.

There are other, less rigorous, methods of achieving the same result, such as SfM and simultaneous localisation and mapping. These methods are favoured by aerial survey methods that use small cameras on smaller aerial platforms such as UAVs.

4.4.4 Orthophotos

Orthophotos are true-to-scale 2D images. A terrain model is used to remove the effects of the aerial camera geometry, tips or tilts in the imagery and the effects of relief displacement. A true orthophoto takes the data processing one stage further by removing the lean on tall buildings, ensuring that the roofs are positioned directly on top of their corresponding building footprints.

True orthophotos can be created in any common imagery format and in any specified coordinate system. The measurement of a distance in the image, such as a road width, will be replicated in the terrain, making them an indispensable tool for a wide range of applications.

4.4.5 Digital terrain/surface models

A terrain model is a digital representation of the ground surface defined by 3D points. Terrain models can be automatically generated from stereo photography. The modelling software takes advantage of the mathematical model established during the aerial triangulation process to calculate a 3D coordinate for each pixel in the stereo imagery.

An alternative method uses a dense image matching (DIM) technique by comparing overlapping imagery row by row to generate a very dense terrain model, creating a dense point cloud.

This technique has largely been adopted for use with aerial photography captured using a UAV platform. These types of survey tend to capture many overlapping images, including obliques, increasing the coverage of the target area.

There are two types of terrain model:

- DTMs, for all points located on the ground and under trees and bridges and
- DSMs, which include all surface features such as the tops of tree canopies and buildings.

Dense point clouds can also be used to create triangulated irregular networks (TINs) of points. A TIN is a representation of a continuous surface consisting of irregular triangular shapes.

Terrain models and TINs are used for a wide range of applications such as:

- 3D city modelling
- 3D visualisation
- forest management
- road, rail and energy sector engineering
- the management of flood risk and

- preventing coastal erosion.

4.4.6 Mapping

Mapping is a traditional application of aerial imagery. Stereoscopic models have a long history of being used to update vector databases for national mapping companies and for engineering applications, among others. Where the third dimension is not required, orthophotos have been successfully employed for map update tasks and land use classification.

5 LiDAR

LiDAR instruments are active sensors that emit and receive a laser pulse from an aerial platform, deducing ranges or distances to the terrain by measuring the time taken for the pulse to return. Coupled with GNSS/IMU technologies, these ranges are used to compute the 3D position of where each laser pulse intercepts the ground below, forming a LiDAR point cloud (see **subsection 5.5.1**) that accurately depicts the terrain below the sensor. Modern LiDAR sensors carry a medium-format RGB camera, enabling imagery to be captured simultaneously.

LiDAR technologies have established themselves as the predominant method of obtaining accurate 3D data from aerial surveys and offer advantages over photogrammetric methods, such as the ability to capture data at night, during the winter, under trees and irrespective of solar angle.

Bathymetric LiDAR systems are typically equipped with dual lasers, with one of them (frequently referred to as a green laser) operating at wavelengths capable of penetrating water. The depth penetration of the bathymetric LiDAR is dependent on the LiDAR system design, the water clarity (normally specified by the water diffuse attenuation coefficient K_d) and the seabed reflectance.

In waters that are clear to the eye, depths of approximately 40m–50m can be reached, but under more common coastal water conditions, 5–20m depth penetration can be expected. The result is an accurate, seamless 3D model of both the land and the sea floor. Typically, the systems also integrate three- or four-band cameras, providing high-resolution RGB plus NIR (RGBN) airborne imaging.

Whether the LiDAR sensor is mounted on a manned aircraft or on a UAV platform, the principles of operation and therefore the guidance below apply in the same way.

5.1 Key considerations

5.1.1 Point density

Laser point density is a key metric when commissioning LiDAR data. Expressed simply as the number of points per square metre (ppm^2), laser point density is a measure of the spatial resolution of the LiDAR data. The higher the point density, the higher the spatial resolution, and therefore more detail will be visible in the data.

The point density is dependent on the laser pulse repetition frequency (PRF, also known as the pulse repetition rate or PRR) and the flying speed. These two variables control the rate of data capture. The PRF is simply the number of times the laser fires every second. The higher the PRF, the higher the achievable point densities. High-specification lasers can fire at a rate of 2MHz.

Slowing down the flying speed of the aircraft will increase the point densities that can be achieved. The flying speed should be slow enough to meet the requirements of the specification, but fast enough to maintain an efficient number of flying hours. In general, flight plans that maximise pulse rate will maximise flying productivity.

The scan rate is the rate at which the data is captured as the laser is directed back and forth (with the use of a mirror), perpendicular to the direction of travel of the aircraft over the terrain. It is not uncommon for the scan rates of high-end systems to operate up to 600 lines per second. The scan rate and FOV is normally adjusted to the selected aircraft speed and flying altitude to achieve as even a point distribution as possible.

Point density is also influenced by the terrain itself. Areas of water will absorb the laser energy, recording very few points unless a bathymetric LiDAR system is used. Vegetation will also absorb a larger amount of the laser energy than artificial surfaces, depending on type; for instance, freshly paved asphalt can have a diffused reflectivity as low as 5%. It is not uncommon for LiDAR specifications to require particular point densities and accuracy with respect to hard surfaces. Point density requirements should be specified, giving a defined minimum target reflectivity; 10% diffuse reflectivity is generally appropriate.

The choice of LiDAR system should be determined by the eventual use for which the data is being commissioned. For example, a flood risk analysis on a large river catchment may require a point density of around $8ppm^2$. This type of project is better suited to the larger LiDAR instruments, where the laser is powerful enough to provide an adequate number of returns from high altitudes, keeping flying time to a minimum and reducing cost.

Corridor engineering applications such as those for road, rail and power line corridors tend to be much smaller but require higher point densities. LiDAR instruments that are eye-safe at low altitudes are more suitable for this type of work.

5.1.2 Point density for bathymetric LiDAR

Point densities for bathymetric LiDAR are normally specified to a 2m × 2m grid, in order to align resolution and accuracies with the International Hydrographic Organization (IHO)'s **S44 Standards for Hydrographic Surveys**.

The losses of laser light in the water are exponential with the depth, and therefore bathymetric LiDAR systems typically operate with much stronger laser pulses, with lower PRF at lower altitudes, typically 400m to 600m AGL.

Optimised for bathymetric capture, they offer a higher point density in shallower waters, with reduced point density in deeper water. Point densities in the range of 12–16 points per 2m × 2m for shallow water and 3–4 points per 2m × 2m for deep water are a typical specification.

Bathymetric LiDAR systems, incorporating both topographic and bathymetric lasers are of course particularly suited for capture of seamless data across the land/water boundary. In the example of floodplain mapping if performed by a bathymetric LiDAR system, not only is the land and the water surface captured, but also the riverbed below, allowing detailed hydrodynamic simulations for flood risk analysis and mitigation.

5.1.3 Field of view

The field of view or data coverage is influenced by:

- the instrument laser scan angle
- the laser power level and
- the flying altitude above the terrain.

More powerful lasers can operate at higher altitudes. The laser scan angle, also referred to as the field of view (FOV) of the instrument, controls the swath width of the laser data coverage on the ground. An FOV of 60° refers to 30° of coverage either side of a nadir line drawn directly below the aerial platform. As the altitude increases, the swath on the ground increases and the point density decreases, as shown in Table 6.

Coverage		**Point density**			**Output**	
FOV (degrees)	**Flying height (m)**	**PRF (Hz)**	**Scan rate (lines/sec)**	**Platform velocity (knots)**	**Point density (ppm²)**	**Capture speed (km²/hr)**
30	30	1×10^5	200	27	448	0.79
30	122	1×10^5	200	27	110	3.28
30	300	1×10^6	200	125	97	36.0
30	1,000	1×10^6	200	125	30	122.4
60	1,300	1×10^6	200	160	8.1	432.0
30	1,300	1×10^6	200	160	17.4	216.0
30	2,800	1×10^6	200	160	8.1	432.0
60	1,300	1×10^6	200	125	10.4	360.0
60	1,300	1.25×10^6	200	125	12.9	360.0

Table 6: Relationship between FOV, flying height, PRF, scan rate, platform velocity, point density and capture rate

Reducing the LiDAR swath on the ground by decreasing the FOV will increase the point density if the laser is fired at the same rate and the aircraft speed is maintained. This will also reduce the capture rate, because less terrain will be covered in the same period. Increasing or decreasing the flying height while maintaining the FOV will influence the coverage area.

An increased point density can be achieved by simply slowing down the aircraft velocity at the expense of reducing the capture rate. Increasing the PRF will also improve the point density while maintaining the capture speed.

5.1.4 FOV for bathymetric LiDAR

Bathymetric LiDAR systems need to accommodate the quadratic losses of laser light as a function of flying altitude, and the exponential losses of laser light as a function of water depth. Therefore, bathymetric LiDAR systems are designed for lower altitude captures at a lower PRF.

A typical specification is shown in Table 7.

Coverage		Point density		Output	
FOV (degrees)	Flying height (m)	PRF (Hz)	Platform velocity (knots)	Point density	Capture speed (km^2/hr)
40	450	Shallow: 1.4×10^5 Deep: 0.4×10^5	125	Shallow: 16 per 2m x 2m Deep: 4 per 2m x 2m	72

Table 7: Typical relationship between FOV, flying height, PRF, platform velocity point density and capture rate for a bathymetric LiDAR system

5.1.5 Directly geo-referencing LiDAR imagery

LiDAR data is scanned line by line as opposed to being captured in a single frame. The scanner head position should be accurately and directly geo-referenced. All LiDAR instruments should have an integrated GNSS/IMU navigation system.

The location of each individual laser pulse at the time of capture is described using three coordinates (easting, northing and height) and three rotations (omega, phi and kappa) around the three principal instrument axes. These systems do require access to GNSS base station data, which can either be data that is captured specifically for the project or that comes from a continuously operating network. Differential correction of the airborne GNSS data can also be achieved during or after the flight using precise orbit information and the PPP technique.

The instrument and point cloud positions can be output in the coordinate system of the client's choice, with available transformations.

A LiDAR system's IMU misalignment angles should be calibrated after a new installation or at a regular interval of one month during a large project. The procedure involves a special flight at two different altitudes.

The flight is used to deduce the angular difference between the LiDAR sensor and the aircraft coordinate systems to ensure alignment. This provides the angular misalignments, which are then applied to the LiDAR data when producing the laser point cloud (see **subsection 5.5.1**).

GCPs are not normally required for this procedure but are useful for quality control of the captured data. Evidence should be provided by the contractor that the GNSS and associated IMU are tested at regular intervals. This is particularly true when the LiDAR components have been removed and reinstalled on the aerial platform.

5.1.6 Calibration

The LiDAR unit should have a factory calibration certificate, valid for a two-year period, prepared by the instrument manufacturer. Several internal sensor parameters should be measured and compared against the values at the time of manufacture. The sensor model should be adjusted accordingly to maintain its accuracy.

It should be noted that some LiDAR system providers offer their customers a full set of automatic LiDAR calibration tools, offering the LiDAR service provider the ability to carry out a full LiDAR calibration of its own.

5.2 Flying and coverage

5.2.1 Flight lines and overlap

Professional flight planning software is used by contractors to consider all the factors affecting point density and will enable coverage of the client's AOI in as few flight lines as possible. The flight planning is completed using an underlying DTM, which takes into consideration the effects of the local topography of the area.

Flight line planning for LiDAR sensors, whether mounted on a manned aircraft or a UAV platform, follows the same principles as those for vertical aerial photography detailed in **subsection 4.2.1**. The best results are achieved by organising the coverage of an area in straight flight lines that are as level as possible. Coverage of corridor features – for example, for transport infrastructure – can be achieved via the use of additional flight lines to capture the bends in the most economical manner.

Overlaps between flight lines are usually at between 10% and 35% and are necessary to ensure that there are no gaps. Cross-strips are also frequently flown to assist in the data processing by tying blocks of flight lines together.

5.2.2 Flight lines and overlap for bathymetric LiDAR

Flight planning bathymetric LiDAR is in many respects like the collection of coastal topographic LiDAR or aerial photography. Following a coastline, the achievable length of the flight lines typically becomes shorter, with the cost of the data capture being related to the complexity of the coastline.

For river surveys, a fixed-wing aircraft cannot efficiently follow all turns of the river, and a significantly larger area than the river alone should be surveyed. Helicopter installations can assist in achieving efficiencies by having a better terrain-following capability.

For some bathymetric LiDAR projects, lines are flown with slightly more than 50% overlap between the flight lines, providing 200% coverage of the area. This is especially optimal for hydrographic object detection/recognition, required for some hydrographic charting applications, particularly where the data is to be used for safety at sea.

5.2.3 Acceptable quality limits

The following list is intended to act as a set of AQLs to provide guidance on the subjective topic of LiDAR data quality. The prevailing weather, environmental and atmospheric conditions, which are outside the control of the contractor, are the most important factors that affect the data quality. The client and contractor should work closely together to ensure a mutually acceptable result.

- Point density and point cloud accuracy specifications should be met for all surfaces having reflectivity greater than the specified minimum.
- Full coverage should be achieved.
- There should be a good match between flight runs.
- The LiDAR should only be flown in good conditions, in the absence of rain, cloud, atmospheric haze, snow and flooding.

- The LiDAR may be flown at any time when the weather conditions are suitable to achieve the specified standards of data quality, except where special time constraints are defined.

Cloud and atmospheric haze are unlikely to affect LiDAR data captured by a UAV platform. However, the other conditions will apply in the same way to achieve good-quality data.

The intended use of the LiDAR may impose limitations on times of flying; see **section 3.3**.

5.2.4 Acceptable quality limits for bathymetric LiDAR

Bathymetric LiDAR data quality is also affected by the water's environmental conditions.

Water turbidity, which is the most critical parameter for bathymetric LiDAR, is normally affected by:

- location
- wind strength and direction on the day of survey
- tides and water level
- river outlets (providing sediments into the water)
- seasonal variations (algae bloom, phytoplankton activities in the water)
- human interaction and pollution in the area
- weather variations
- vulnerability of the seabed
- water flow (in river environments)
- breaking waves and
- foam/bubbles in the water.

Further environmental factors that affect the results are:

- local seabed reflectance and
- seabed vegetation (including stage of growth).

Understanding the local tidal constraints (see **subsection 3.3.4**) is also key to improving data quality, particularly with reference to establishing the correct vertical datum.

5.3 LiDAR accuracy and resolution table

Table 8 is based on the American Society for Photogrammetry and Remote Sensing (ASPRS) document **ASPRS Positional Accuracy Standards for Digital Geospatial Data**, edition 1, version 1.0., 2014, p.A7.

The accuracy values in the table are dependent on:

- the flying altitude and
- the GNSS positional and IMU angular rotation errors of the equipment used.

Laser ranging and timing errors are also considered. Many other factors may also affect accuracy and resolution. Therefore, the values quoted can only be referenced as achievable.

Platform	Height AGL (m)	Height AGL (ft)	Achievable accuracy RMSE for plan X, Y (m)	Achievable accuracy RMSE for height Z (m)	Achievable resolution (ppm^2)
UAV	30	100	±0.02	±0.02	208
UAV	122	400	±0.06	±0.05	51
Helicopter	260	853	±0.03	±0.03	100
Helicopter	400	1,312	±0.04	±0.03	48
Fixed-wing	500	1,640	±0.04	±0.03	30
Fixed-wing	725	2,379	±0.06	±0.04	20
Fixed-wing	1,300	4,265	±0.10	±0.05	8
Fixed-wing	2,600	8,530	±0.20	±0.10	2
Fixed-wing	5,000	16,404	±0.39	±0.15	1

Table 8: Achievable accuracy and resolution values for LiDAR sensors

The altitude of 400ft represents the highest at which a UAV can be flown in the UK without the approval of an operational safety case.

For comparison purposes, the LiDAR FOV was maintained at 60°, keeping a high degree of coverage. LiDAR resolutions were calculated from first principles. The laser PRF values vary with altitude as lasers with a high PRF capability currently tend to be larger and heavier and can therefore only be carried by fixed-wing and helicopter platforms. The differences in platform velocity at different altitudes were also considered when calculating the LiDAR resolution.

5.4 LiDAR accuracy and resolution for bathymetric LiDAR

Accuracy specifications for bathymetric LiDAR are typically given at a 95% confidence level rather than by RMSE values. This is in order to align with standard hydrographic specifications. For all bathymetric LiDAR data accuracies, there is also a depth-dependent component, as several of the uncertainties vary with water depth.

The IHO **S44 Standards for Hydrographic Surveys** provides the following accuracy classes of relevance for bathymetric LiDAR.

Criteria	Order 1b	Order 1a	Special order
Area description	Areas where the under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area.	Areas where the under-keel clearance is considered not to be critical, but there may be features of concern to surface shipping.	Areas where the under-keel clearance is critical.

Criteria	Order 1b	Order 1a	Special order
Total horizontal uncertainty (THU) 95% confidence interval	5m + 5% of depth	5m + 5% of depth	2m
Total vertical uncertainty (TVU) 95% confidence interval	TVU = $\sqrt{a^2 + (D * b)^2}$ Where: a = 0.5m b = 0.013 D is the depth in metres	TVU = $\sqrt{a^2 + (D * b)^2}$ Where: a = 0.5m b = 0.013 D is the depth in metres	TVU = $\sqrt{a^2 + (D * b)^2}$ Where: a = 0.25m b = 0.0075 D is the depth in metres
Feature detection	Not specified	Cubic features >2m in depths down to 40m	Cubic features >1m
Feature search	Recommended but not required	100%	100%
Bathymetric coverage	5%	≤100%	≤100%

Table 9: Achievable accuracy values for bathymetric LiDAR sensors

Most bathymetric LiDAR surveys are specified on requirements based on IHO Order 1b or IHO Order 1a with additional LiDAR-specific features. Regardless of IHO category used, bathymetric LiDAR object detection cannot be guaranteed to the full-depth extension of the LiDAR due to the optical properties of water. It is important to consult with the intended LiDAR service provider in advance on accuracies and object detection capabilities as these are dependent on both the system and the prevailing water conditions.

5.5 LiDAR deliverables and products

5.5.1 LiDAR point cloud

The basic deliverable is the LiDAR point cloud, which is made up of individual laser data points that are fully geo-referenced in 3D in the client's choice of coordinate system and usually cut into 1km squares.

LAS (or the compressed version, LAZ) is the most frequently used format for LiDAR data. It is an internationally used standard format, maintained by the ASPRS, which facilitates data classification and storage of metadata.

The client may specify the data format, data compression and data transfer medium. As with aerial photography, LiDAR data at high point densities can require large volumes of disk space, so clients are likely to specify a format that can be easily incorporated into their archive system.

5.5.2 Metadata

Metadata may be specified for LiDAR or for any other LiDAR products. The LiDAR LAS format promotes the easy management and exchange of metadata, and includes the following attributes:

- date and time flown
- GNSS (for example, GPS) time
- geographic reference
- flying height
- coordinate system
- geodetic datum
- scan angle
- colour attributes (RGB or RGBN; that is, three- or four-band)
- number of returns and
- laser intensity (normalised or reflective).

5.5.3 Digital terrain/surface models

The LiDAR point cloud can be processed to extract a ground class and a second class containing all points above the ground. The ground class can be extracted separately to create a DTM of the AOI. A DSM can be created by combining the ground class and the above-ground class into a single file.

5.5.4 Classified point clouds

Classified point clouds further categorise the data into separate groups. The points above the ground, for example, can be classified into:

- buildings
- hard surfaces
- water surface
- lampposts
- power supply lines and
- areas of low, medium and high vegetation.

It is also common to remove temporary movable objects such as cars and classify these as noise. This enables further specialist analysis of the data. The LAS format sets out several standard classes within this specification.

Where an RGB camera has been flown simultaneously with a LiDAR instrument, it is possible to assign the RGB colour value from the camera to each individual LiDAR point in the point cloud. These colourised point clouds offer a more realistic representation of the AOI.

5.5.4 Classified point clouds for bathymetric LiDAR

For bathymetric LiDAR the following classes are typically required:

- water surface points
- derived water surface (water surface used for water refraction correction)
- seabed points
- hydrographic objects and
- seabed vegetation.

5.5.5 Mapping

Topographic mapping in 3D vector format can be extracted from LiDAR point clouds. The linework is digitised from the data in 2D, frequently with the use of a simultaneously captured imagery layer or from the intensity/reflectance data. Heights are then assigned to the 2D feature strings by draping the linework onto the 3D point cloud. This approach has been successful for high-accuracy engineering applications.

More recent software developments have allowed the extraction of building models at Level of Detail (LOD) 2 directly from the point cloud data. This can be accomplished using either a priori building footprint files (for example, from an existing GIS database) or without any a priori data.

6 Hyperspectral, multispectral and thermal imaging sensors

Aerial survey sensors operating in the non-visible parts of the electromagnetic spectrum offer a rich source of data from which to extract information through sophisticated spectral analysis. When using these sensors, the emphasis tends to be on detection, classification and identification, and the condition of features, rather than their absolute position. These sensors broadly fall into three categories: thermal, multispectral and hyperspectral. In recent years, the use of UAVs for precision agriculture has been an important factor in driving the development of small-format multispectral and hyperspectral cameras.

Thermal imaging

Thermal cameras operate in the infrared part of the spectrum at wavelengths of 4–12 microns. They can sense heat energy emitted, reflected or transmitted by an object. A good-quality, well-calibrated sensor can have a measurement accuracy of ±1°C. They have found applications in the power industry and in housing energy efficiency surveys.

Multispectral imaging

Multispectral cameras typically sense in between three and ten separate bands, depending on the application of the data. The focus is on multiple, specific wavelengths as opposed to traditional imaging that involved broad spectral ranges. Band-pass filters are used to filter out unwanted frequencies. A common configuration is the use of three bands (visible green, visible red and an NIR band), which finds applications in determining plant and soil water saturation.

The processing of multispectral data can be complex and requires the specialist knowledge of a spectral analyst.

Hyperspectral imaging

Hyperspectral sensors cover the broadest spectral range of all non-visible sensors. A high-quality instrument or combination of sensors can typically sense from 380mm to 2,500nm, from the ultraviolet through visible to visible near-infrared (VNIR) and to the short-wave infrared (SWIR) parts of the electromagnetic spectrum.

These instruments are also characterised by the large number of spectral bands that they can use to separate the data, typically more than 500. With such a rich data source, the applications are bespoke, numerous and varied, including:

- the detection of invasive plant and insect species
- precision agriculture and
- the detection of minerals.

As for multispectral sensors, the processing and manipulation of this data requires the specialist knowledge of a spectral analyst.

6.1 Key considerations

6.1.1 GSD

GSD is a key metric specified by the contractor when commissioning hyperspectral, multispectral, or thermal imaging projects. As for aerial imagery, the GSD of any hyperspectral, multispectral or thermal imaging mission is determined by the flying altitude, the dimensions of the camera sensor chip and the lens.

However, when using hyperspectral, multispectral and thermal imaging sensors, improving the spatial and spectral resolution can increase the amount of noise in the signal. It is therefore not uncommon for GSDs of 0.5m or even 1m to be used, with the emphasis on feature identification and condition.

6.1.2 Directly geo-referencing hyperspectral, multispectral and thermal imagery

Hyperspectral, multispectral and thermal imaging sensors are passive sensors, relying on radiation from the sun reaching the camera head, or in the case of a thermal sensor, being emitted from the target. Both push-broom and frame sensors are available, although the former are becoming less common for multispectral and thermal imaging sensors.

Hyperspectral sensors are typically of a push-broom design relying on a prism to separate the wavelengths and focus them on to a single cross-track line, building up the image line by line.

They do rely on an accurate GNSS/IMU navigation system to directly geo-reference the imagery, similar to the systems described in **subsections 4.1.5** for aerial photography and **5.1.5** for LiDAR sensors.

It may be necessary to document the sensor models used to transform coordinates on the sensor device to coordinates on the Earth's surface. Should a requirement arise to document the sensor models, the following specifications may be used to describe them:

- **OGC 12-000**, OGC® SensorML: Model and XML Encoding Standard and
- **OGC 17-011r2**, JSON Encoding Rules SWE Common/SensorML.

6.1.3 Calibration

Hyperspectral, multispectral and thermal imaging sensors are sensitive precision instruments. The quality of the data captured is very dependent on ensuring that the instruments are calibrated regularly according to the instrument manufacturer's guidelines.

As with aerial photographic cameras and LiDAR sensors, a calibration flight is necessary every time the instrument is installed in a new aircraft to establish the relationship between the aircraft and the sensor/IMU coordinate system.

6.2 Flying and coverage

6.2.1 Flight lines and overlap

As with LiDAR imagery, professional flight planning software is used by contractors.

Flight line planning for hyperspectral, multispectral or thermal imaging sensors follow the same principles as for vertical aerial photography detailed in **subsection 4.2.1**.

Overlaps between flight lines, usually at between 15% and 35%, are necessary to ensure that there are no gaps.

6.2.2 Flight times

Thermal imagery does not rely on the capture of the visible parts of the electromagnetic spectrum, and therefore it can be captured at night. Indeed, this is recommended, because air temperatures are then cooler and more stable, while noise-inducing solar reflections are not present, meaning differences in temperature are easier to detect. Thermal imagery is frequently commissioned during the winter period for the same reasons.

Multispectral imagery is frequently commissioned for the study of vegetation health and land use cover, and as such it is usually captured during the main part of the flying season when the vegetation is in full bloom and under consistent illumination.

Hyperspectral imaging sensors require the best conditions possible to detect enough energy to produce good-quality results. This usually means operation with a high solar angle in bright sunshine and cloudless skies. The presence of a significant amount of moisture in the air will affect the returns in the SWIR part of the electromagnetic spectrum.

6.2.3 Acceptable quality limits

The following list is intended to act as a set of AQLs to provide guidance on the subjective topic of image quality. The client and contractor should work closely together to ensure a mutually acceptable result.

- Geospatial and spectral resolution specifications should be met.
- Full coverage should be achieved.
- There should be a good match between flight runs and adjacent images.
- Hyperspectral, multispectral and thermal sensors should only be flown in good conditions, in the absence of rain, cloud, atmospheric haze, snow and flooding.
- Hyperspectral sensors are particularly sensitive to moisture in the atmosphere and should only be flown in bright sunshine and cloudless skies.

The intended use of the data may impose limitations on times of flying. See **section 3.3**.

6.3 Hyperspectral, multispectral and thermal imagery resolution table

The emphasis of aerial surveys operating in the non-visible part of the electromagnetic spectrum has been on feature identification and condition.

Table 10 was prepared from first principles, focusing on the achievable spatial resolutions.

Platform	Height AGL (m)	Height AGL (ft)	Achievable resolution for thermal – GSD (m)	Achievable resolution for multispectral – GSD (m)	Achievable resolution for hyperspectral – GSD (m)
UAV	30	100	0.07	0.01	0.02
UAV	122	400	0.28	0.06	0.08
Helicopter	270	886	0.05	0.14	0.19
Fixed-wing	500	1,640	0.10	0.25	0.36
Fixed-wing	1,000	3,281	0.20	0.50	0.71
Fixed-wing	2,000	6,562	0.40	1.00	1.43
Fixed-wing	3,000	9,842	0.60	1.50	2.14

Table 10: Achievable resolution values for thermal, multispectral, and hyperspectral imagery

The UAV altitude of 400ft represents the highest at which a UAV can be flown in the UK without the approval of an operational safety case. The higher-performing thermal imaging cameras tend to be larger and heavier, and therefore at present can only be carried by fixed-wing and helicopter platforms.

6.4 Hyperspectral, multispectral and thermal imagery products

6.4.1 Thermal imagery

The most common product created from thermal imagery is an orthorectified mosaic created from the individually captured thermal images. In a mosaic, the individual pixels have values that reflect the relative temperatures across the AOI. The orthorectification process ensures that accurate measurements are possible from the imagery.

Thermal imagery has found applications in monitoring energy usage over wide areas and pinpointing inefficient assets such as individual buildings and pipelines.

6.4.2 Multispectral imagery

Multispectral imagery is a rich source of information, from which can be extracted bespoke terrain characteristics, particularly relating to plant health.

The simplest products created from multispectral imagery are three- and four-band orthorectified images. Colour–infrared (CIR) photography combines the red and green visible bands with the infrared. Intense reds in this imagery are associated with healthy vegetation, showing fast growth rates.

Four-band imagery – combining the visible RGB bands with the NIR band – has all the benefits of traditional imagery, with the additional advantage that the latter band can be used for vegetation studies.

The normalised difference vegetation index (NDVI) is another common multispectral imagery product, using a simple derived index value to differentiate between rock, sand and vegetation-rich areas such as temperate or tropical forests.

Creating products from ten-band multispectral cameras is much more complex. The successful analysis of this data relies on the creation of a spectral signature of the landscape feature in the terrain that the user wishes to detect.

A spectral signature is the variation in the electromagnetic reflectance of a homogeneous target across several different wavelengths. Spectral signatures are unique responses for each land cover classification, such as sand, roads, cereal crops, grassland, moorland or forestry. They are created using a combination of multispectral observations from the camera and observations on the ground, known as ground-truth observations. Using a predefined spectral signature, an automatic classification is run on the imagery to identify the target object such as the area of cereals under cultivation.

The spectral signature for each land cover will be different depending on solar radiation, and will vary with the season of the year and location on the planet. This makes building a spectral library a difficult task.

6.4.3 Hyperspectral imagery

The principles behind hyperspectral imagery classification are the same as for multispectral imagery, in that a spectral signature is used to classify and extract the landscape feature under study.

Hyperspectral data is captured in a wide range of the electromagnetic spectrum (2,120nm) that can be split into more than 500 individual spectral bands; this improves the precision and the number of data processing possibilities. However, a lot more effort and attention is required when completing the ground-truth observations, which should include handheld spectrometer observations.

In the more traditional area of vegetation analysis, hyperspectral imaging has the potential not just to identify cereals but also to differentiate between wheat and barley, for example.

Hyperspectral imaging has found applications in:

- invasive species detection
- forestry inventories
- the estimation of soil water content
- geological applications and
- mineral exploration.

7 Earth observation

Earth observation from satellite platforms offers the advantage of covering large areas, up to 1,000,000km^2 every day.

Sensors on board satellite platforms tend to have either a push-broom scanner, also known as an along-track scanner, or a whisk-broom scanner, also known as an across-track scanner. Both types of scanner can produce both mono and stereo imagery. Whisk-broom scanners have a greater number of moving parts, which tends to make the design of these instruments heavier, more expensive and more prone to wearing out than their push-broom counterparts. However, the whisk-broom design does have the potential to offer a better spatial resolution.

Scanner-based imagery should be flown in a continuous swath with a minimum of 20% overlap (25% in elevated or urban areas).

The key decision is whether the client's specification requires new imagery to be commissioned, or can be fulfilled from the archives of satellite imagery providers. With tasked imagery, the same point on the Earth's surface can potentially be revisited daily, offering monitoring solutions as well as applications in mapping, change detection and responding to environmental disasters.

7.1 Types of imagery

Visible, radar and multispectral sensors are the most common kinds used on satellite platforms. It is common for individual satellites to carry multiple sensors, including panchromatic, RGB and NIR kinds, and additional multispectral options.

Radar imaging relies on an active sensor emitting electromagnetic radio waves. Unlike optical methods that measure the wave amplitude, radar sensors measure the phase of the backscattered active radio waves, and can therefore operate in the dark and in all weather conditions.

Modern satellite sensors offer spatial resolutions of between 0.35m and 1.5m GSD for panchromatic sensors and from 1m to 6m GSD in the multispectral bands. Active radar sensors can offer imagery resolutions of between 1m and 5m.

7.2 Flying and coverage

7.2.1 Satellite orbits

Earth observation satellites typically operate in sun-synchronous, geostationary or polar orbits. Geostationary orbits are at altitudes of approximately 36,000km, where the satellites take around 24 hours to orbit the Earth. This enables continent-wide areas to be monitored continuously for environmental conditions or weather patterns.

Polar orbits are the most common for remote sensing applications. In such an orbit, the satellites pass within 20° to 30° of the poles. Typically passing over the polar regions several times a day, they are at an altitude of between 200km and 1,000km from the Earth's surface. The cameras on board the satellites can be tasked with capturing either nadir imagery or off-nadir imagery.

When using off-nadir imagery, the imagery sensor is rotated so that it views the AOI from the side, rather than waiting until the satellite is directly overhead. This reduces the length of time that will elapse between observations, known as the satellite revisit time. However, because of the greater distance between the sensor and the surface of the Earth, off-nadir imagery results in poorer resolution than nadir imagery.

7.2.2 Acceptable quality limits

The following list is intended to act as a set of AQLs to provide guidance on the subjective topic of image quality. The client and contractor should work closely together to ensure a mutually acceptable result.

- The specified coverage and imagery accuracy requirements should be met.
- The imagery should be sharp.
- Colour, contrast and light balance should be uniform across the whole AOI. This is particularly true for stereo photography.
- The time lapse between stereo pairs should not be so great as to affect the quality of the stereo models.
- The imagery should only be accepted if it is substantially free of cloud, dust, atmospheric haze, dense shadow or smoke. Isolated areas of cloud, dense shadow or smoke should not be cause for rejection of the imagery provided the intended use is not impaired. Typical tolerances for cloud and cloud shadows may be less than 5% or 10% in a single image.
- The photography should conform to any specific radiometric values specified by the client, including:
  - mean histogram luminosity values
  - mean of the individual colour bands and
  - standard deviation for each colour band.

The photography may be captured at any time when the weather conditions are suitable to achieve the specified standards of image quality, except where special time constraints are defined.

Earth observation satellites operate on specific orbits and cross the equator at the same time every day. It is therefore not possible to capture data over a target at a specific time of day. The intended use of the imagery may impose limitations on times of capture. For Earth observation imagery, it is common to specify winter or seasonal imagery capture, acquiring photographs when trees are not in leaf, or during a part of the growing season.

7.3 Earth observation accuracy and resolution tables

Table 11 shows the achievable accuracy and resolution values for visible satellite imagery.

Platform	Height AGL (km)	Height (miles)	Achievable accuracy RMSE for plan X, Y (m)	Achievable accuracy RMSE for height Z (m)	Achievable resolution –GSD (m)
Satellite imagery	450–770km	279–478 miles	3–4m (CE90)	3–4m (LE90)	0.35–0.8

Table 11: Achievable accuracy and resolution values for visible satellite imagery

Achievable accuracies are quoted as circular and linear errors (CE and LE), at the 90% confidence level.

Table 12 shows the achievable resolution values for multispectral and hyperspectral imagery captured from a satellite platform.

Platform	Height AGL (km)	Height AGL (miles)	Achievable resolution for multispectral – GSD (m)	Achievable resolution for hyperspectral – GSD (m)
Satellite hyperspectral and multispectral imagery	450–770km	279–478 miles	1–6	1.25–3.7

Table 12: Achievable resolution values for hyperspectral and multispectral satellite imagery

Table 13 shows the achievable resolution values using an active radar instrument, from a satellite platform.

Platform	Height AGL (km)	Height AGL (miles)	Achievable resolution (m)
Radar imagery (SAR)	514–693 km	321–433 miles	1–5

Table 13: Achievable resolution values using radar satellite imagery

7.4 Satellite imagery products

7.4.1 Stereo imagery

Imagery from satellite platforms can be formed into stereo models. These are created from pairs of images captured from the same orbit at different times and the associated camera model and geo-referencing information. Using this imagery requires specialist software with advanced image processing and photogrammetric tools.

Stereo imagery finds applications in the creation of DTMs, DSMs, mapping and 3D visualisation.

7.4.2 Orthophotos

Satellite imagery providers frequently offer processed imagery in the form of orthophotos, where the rectification to create the true-to-scale 2D imagery has already been completed.

They can be created in any common imagery format, in any specified coordinate system, assuming suitable transformations are available. The measurement of a distance in the image (such as a road width) will be replicated in the terrain, making them an indispensable tool for a wide range of applications, such as the extraction of mapping and thematic layers for GIS analysis.

7.4.3 Multispectral and hyperspectral imagery

Multispectral and hyperspectral imagery from satellite platforms offer the same set of products as from a manned aircraft or a UAV (see **sections 6.4.2** and **6.4.3**), with the obvious advantage of a potentially much larger area of coverage captured in a shorter time span.

As well as the traditional three- and four-band orthorectified products, modern satellite multispectral sensors offer a wider range of spectral bands than their aerial counterparts, which can be automatically classified in the same way using a spectral signature.

It is particularly important in this scenario to verify the accuracy of the spectral analysis with ground-truth observations.

7.4.4 Synthetic aperture radar

SAR operates in the microwave part of the spectrum, using an active sensor. This technique measures the phase between the emitted radar pulse and its echo from the terrain to create the high-resolution images of the Earth's surface.

SAR imagery can be captured at night, and through thin cloud and thick vegetation layers.

SAR imaging has been used in digital elevation model (DEM) generation as well as in land management, crop classification, geological applications, and monitoring change such as urban growth and deforestation.

Interferometric SAR (InSAR) is a technique that uses pairs of radar images to generate maps of surface deformations. These are generated by the analysis of the differences of the waves returning to the satellite or aircraft-based instrument.

This technique has found applications in the structural monitoring of dams, buildings, bridges, monitoring subsidence, and monitoring earthquake and volcanic activity.

8 Future developments

8.1 Sensor miniaturisation

UAVs have gained acceptance in the aerial survey industry due to the improvement in their ability to carry more complex survey-grade sensors. The trend in miniaturisation of navigation and LiDAR sensors for UAV deployment is set to continue.

8.2 Sensor fusion

Along with miniaturisation has come sensor fusion, where aerial survey instruments incorporate more than one data type. A common option is the combination of nadir and oblique cameras with a high-powered LiDAR sensor in the same instrument. The flying advantages are clear: three data types are captured on a single mission, each co-registered with the others using the same navigation dataset.

This multi-sensor approach also offers advantages during the data processing stage, with the combination of dense point cloud DSM generation fused with LiDAR data, offering better-quality height and 3D modelling products.

8.3 Beyond visual line of sight UAV operation

The development of safety cases to enable beyond visual line of sight (BVLOS) operation is another key area. True BVLOS flights should occur once UAVs are able to communicate autonomously with other airspace users and automatically sense and avoid other flying objects. The benefits of BVLOS will be fully realised once the flight times of UAVs are increased with improved battery technologies. This capability is expected to benefit fixed-wing UAVs more than multi-rotor UAVs, as they have a much longer flight time.

8.4 LiDAR developments

Geiger-mode LiDAR (GML), single-photon LiDAR (SPL) and flash LiDAR are examples of developments that are currently being refined.

GML and SPL have a sensor design that is based on a focal plane array of pixels; this is opposed to the single pixel that is used in traditional LiDAR technology, known as linear LiDAR. These technologies divide a single pulse into hundreds of thousands of sub-pulses providing broad flashes of laser illumination on the terrain below, offering potentially higher point densities.

GML and SPL also require less laser energy per illuminated detector, enabling them to be flown at higher altitudes while maintaining effective pulse rates, therefore achieving higher coverage and/or point densities and reducing costs.

Flash LiDAR, while offering higher point densities, is a relatively high-energy system, making it more suitable for low-altitude applications. It is unclear whether any of these developments will gain the market that linear LiDAR currently enjoys; linear LiDAR still offers advantages in vegetation penetration and accuracy.

8.5 High-altitude pseudo satellites

The development of high-altitude pseudo satellites (HAPS) offer a different Earth observation platform, at altitudes of between 20km and 50km AGL. These unmanned lightweight platforms use the latest in sensor miniaturisation and are solar-powered. They currently have a flight endurance of up to three months.

8.6 Developments in satellite technology

Owning and operating an Earth observation satellite constellation is no longer the preserve of nation states. Modern satellite technologies are much smaller, enabling increased capture options at additional times and places, and the ability to undertake repeated observation and monitoring daily.

An increased number of Earth observation satellites in orbit, together with improving sensor capabilities, will increase the number of use cases from space in the future.

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Appendix A: Sample specifications

The following four tables are basic examples of sample specifications for aerial photography, LiDAR, thermal imagery and RGB Earth observation imagery. In each instance, the use case for the data is stated.

Item	Aerial photography
Use case	National mapping
Accuracy	0.4m RMSE
Resolution (GSD)	0.15m
Coverage	As per supplied digital file
Project constraints	Capture imagery at low tide
Metric camera (Y/N)	Y
Stereo imagery overlaps	60%
Flight line overlaps	30%
Data AQLs	The imagery should be sharp. Flare from large expanses of glass, water or cars should be at a minimum. Colour and light should be uniform. Contrast across the block should be consistent. There should be a good match between individual flight runs and adjacent images. The photography should only be flown in conditions where the visibility does not significantly impair the image quality and detail.
Solar angle	Above 15°
Deliverables	Orthophotos at 0.15m GSD

Table A1: Sample specification for aerial photography

Item	LiDAR
Use case	Railway engineering
Accuracy	0.04m RMSE
Coverage	As per supplied file
Project constraints	Urban area air traffic control
FOV	50°
Data AQLs	The LiDAR should only be flown in good conditions, in the absence of rain, cloud, atmospheric haze, snow and flooding.
Solar angle	No restriction
Point density	48ppm^2
Deliverables	Point cloud, DTM and DSM

Table A2: Sample specification for LiDAR

Item	Thermal imagery
Use case	Energy efficiency study
Accuracy	1m RMSE
Resolution (GSD)	0.5m
Coverage	As per supplied file
Start and end date	Winter period
Project constraints	Urban area air traffic control
Equipment calibration records	Request instrument calibration records
Data quality AQLs	Has to be flown at 4°C, with maximum wind of 3m/s or slower. There should have been no rain in the previous 24 hours. The flight should take place between 19:00 and 23:00.
Solar angle	No restriction
Spectral band identification	Thermal band (3.6–4.9 microns)
Products/deliverables	Orthorectified thermal imagery (0.5m GSD)

Table A3: Sample specification for thermal imagery

Item	Earth observation
Use case	Land cover classification
Accuracy	<4m CE
Resolution (GSD)	0.55m
Coverage	As per supplied file
Start and end date	Summer capture
Project constraints	Capture within peak growing season
Stereo imagery overlaps	60%
Flight line overlaps	20%
Data AQLs	Maximum 5% cloud; imagery to be free from dust and artefacts.
Spectral band identification	RGB imagery
Tasked imagery	Yes
Nadir angle	Better than 20°
Products/deliverables	RGB orthophotos at 0.55m GSD

Table A4: Sample specification for Earth observation

Appendix B: Combined platform, altitude, data type and achievable accuracy

Table B1 combines the detail from **sections 4.3**, **5.3**, **6.3** and **7.3** into a single table.

Platform	Height (m)	Height (ft)	Achievable accuracy for plan X, Y (m)	Achievable accuracy for height Z (m)	Example survey types/uses
UAV	30	100	0.01	0.02	Imagery and LiDAR for heritage recording, and construction monitoring Multispectral imagery for precision agriculture
Helicopter	319	1,047	0.03	0.04	High-accuracy engineering design – road, rail, power networks
Helicopter	638	2,093	0.06	0.08	Engineering asset management Mapping telecommunications networks
Fixed-wing	1,300	4,265	0.06	0.08	Building information modelling (BIM) for infrastructure Imagery for cadastral mapping LiDAR for forestry Multispectral biomass mapping, monitoring the health of plants and crops Hyperspectral tree species mapping, soil moisture content
Fixed-wing	2,600	8,530	0.14	0.18	Imagery for urban mapping and 3D city models Imagery and LiDAR for coastal management Thermal mapping for energy efficiency surveys and detecting pollution
Fixed-wing	4,500	14,764	0.23	0.30	Imagery for rural mapping Imagery and LiDAR for river catchment flood risk management
Fixed-wing	7,500	24,606	0.38	0.50	Imagery for upland area mapping and environmental impact assessment
Satellite	450–770km	279–478 miles	3–4m (CE90)	3–4m (LE90)	Satellite imagery for land cover classification Multispectral satellite imagery for environmental monitoring and vegetation index mapping

Table B1: Combined platform, altitude, data type and achievable accuracy

Notes:

- Achievable accuracies are quoted in RMSE figures relative to ground control apart from satellite imagery, which are quoted as circular and linear errors (CE and LE), at a 90% confidence level.
- All quoted absolute accuracies are relative to control accuracy (ground and/or airborne) and possible inherited GNSS inaccuracies. Users should refer to **section 3.4** and the current edition of **Guidelines for the use of GNSS in land surveying and mapping**, RICS guidance note. For example, the quoted achievable relative accuracy for UAVs (±10mm X,Y) would require absolute ground control of the order of three times better (±3mm), which would be difficult to achieve.
- The quoted achievable accuracies are not valid for the example survey types and uses using non-visible forms of remote sensing, except for multispectral satellite imagery. Further details can be found in **section 6.3**.
- This table can be directly related to the current edition of **Measured surveys of land, buildings and utilities**, RICS guidance note. A new edition is planned, and it is expected that the information in Table B1 will be integrated into a new geospatial survey accuracy banding table in due course.

Appendix C: Glossary

Absolute accuracy	The measurement of RMSE for normally distributed error vectors, relative to a defined coordinate grid and/or height datum. This is typically measured from the nearest survey control marker, commonly established by high-precision static GNSS, which was used in setting up the primary grid.
Accuracy (spatial measurement)	Accuracy of a survey measurement used to quantify the possible difference between an actual dimension, size, relative position or location and the measurement value (**BS 5606**).
Active sensor	An instrument that both emits and receives reflected energy from the terrain and the responses recorded at the onboard instrument. LiDAR is an active sensor.
Aerial photography	Photographs taken from an aerial vantage point.
Aerial triangulation	The process by which stereo photography is tied together to form stereo models and geo-referenced to ground control points.
Ambiguity	The unknown integer number of carrier phase cycles in an unbroken set of GNSS measurements.
American Society for Photogrammetry and Remote Sensing (ASPRS)	An international scientific association aiming to advance knowledge of mapping sciences and promote the responsible application of photogrammetry, remote sensing, geographical information systems and supporting technologies.
Angular misalignment	The misalignment between the survey instrument reference frame and the aircraft reference frame.
Base line	The 3D vector distance between the GNSS receiver on a moving aerial platform and a ground GNSS base station.
Bathymetric survey	The measurement of the depth of a water body as well as the mapping of underwater and intertidal terrain.
Calibration	The procedure by which aerial survey instruments are checked and adjusted to ensure consistency of the resulting measurements.
Charge-coupled device (CCD)	An electronic chip employed in digital cameras to measure light intensity.

Circular error (CE)	A term commonly used to represent the horizontal accuracy of Earth observation imagery. A value of CE (90) 5m represents a circular error where a minimum of 90% of the points measured have a horizontal error of less than 5m.
Civil Aviation Authority (CAA)	The government organisation responsible for all aspects of civil aviation in the UK.
Coordinate reference system	A mathematical definition of a coordinate system, including the origin, scale, position and orientation of the reference ellipsoid.
Cross-strip	A strip of aerial photography or LiDAR data flown at 90° to the main block, in order to tie blocks of flight lines together and improve block geometry.
Cycle slip	The loss of lock of the satellite signal by a GNSS receiver.
Dense image matching (DIM)	A photogrammetric technique that enables the extraction of 3D surfaces from images acquired from multiple views.
Digital twin	A realistic digital representation of assets, processes or systems in the built or natural environment.
Earth observation	The process of capturing data about the Earth's physical, chemical and biological systems using remote sensing technologies, including surveying techniques and the collection, analysis and presentation of this data.
Elevation	The height above a defined level datum, e.g. mean sea level.
Elevation mask	The lowest elevation in degrees above the horizon at which a GNSS receiver is set to track a satellite.
Ellipsoid	In geodesy, a mathematical figure formed by revolving an ellipse about its minor axis to describe the shape of the Earth. Used interchangeably with spheroid.
Ellipsoidal height	The height between a point on the ellipsoid and the topographic surface.
Ephemeris	A set of data that describes the position of a celestial object as a function of time.
Epoch	A point in time that is the reference for a set of coordinates.
European Union Aviation Safety Agency (EASA)	The European authority in aviation safety.
Focal length	The distance between the centre of a lens and its focal point.

Forward motion compensation (FMC)	A technique used to compensate for the forward motion of an aircraft during the capture of an aerial image.
Geodetic datum	A precise mathematical model designed to best fit part or all of the geoid.
Geo-referencing	Referencing an image, point cloud, vector data or other entity by its geographical coordinates.
Geoid	The equipotential surface that most closely approximates to mean sea level. This surface is everywhere perpendicular to the force of gravity.
Geoidal separation	Difference in height between the ellipsoid and the geoid.
Global navigation satellite system (GNSS)	Encompasses **all satellite systems that are used for navigation purposes** including GPS, GLONASS, Galileo and BeiDou.
Ground-resolved distance (GRD)	The minimum detectable distance between two small features on the ground.
Ground-sampled distance (GSD)	The distance between the centres of two consecutive pixels on the ground. GSD is a common way to define the resolution of Earth observation and aerial imagery.
Gyro-stabilised mount	An aerial camera mount that is held constantly in a horizontal position during flight using a gyroscope and an inertial measurement unit (IMU).
Hyperspectral imagery	An imaging technique operating across the visible and non-visible parts of the electromagnetic spectrum, typically recording reflected and emitted electromagnetic radiation in very narrow bands.
Inertial measurement unit (IMU)	An electronic device capable of measuring the gravitational and acceleration forces on a moving vehicle and reporting its velocity and position.
Interferometric synthetic aperture radar (InSAR)	The measurement of the differences in the phases of the waves between two SAR images acquired over the same area at different times.
Kinematic survey	A dynamic method of GNSS positioning using carrier phase observations in which one receiver is moving (typically on an aerial platform) and one or more base station receivers are stationary.
LAS file format	A common LAS (LASer) point cloud file format specified by the ASPRS. LAZ is the compressed version of the same format.

Linear error	A term commonly used to represent the vertical accuracy of Earth observation imagery. A value of LE (90) 5m represents a linear error where a minimum of 90% of the points measured have a vertical error of less than 5m.
Metadata	A set of data that describes and stores information about other data.
Metric camera	A camera for which the focal length and radial and tangential distortions are known and calibrated regularly.
Mosaic	An assembly of digital images that have been carefully cut and joined to produce a composite image of an area of terrain larger than could be covered in a single aerial photograph at the same scale.
Multispectral imagery	Imagery captured using sensors operating outside the visible part of the electromagnetic spectrum.
Nadir	The point on the Earth directly below the observer.
Oblique photography	Aerial photography taken from an off-nadir position.
Operational authorisation	A risk-based approach to providing the necessary risk assessment and safety case information for safe UAV operations.
Orthometric height	Height between a point on the geoid and the topographic surface, also known as mean sea level.
Orthophotography	The use of digital rectification and digital elevation models to produce an image that has a consistent scale.
Panchromatic imagery	Images created using an imaging sensor that is sensitive to all radiation in the visible region of the spectrum.
Passive sensor	An instrument that receives and records reflected energy from the sun. A hyperspectral instrument is a passive sensor.
Permission for commercial operations (PfCO)	The legal document needed to operate a drone commercially in UK airspace.
Photogrammetric six degrees of freedom	The six values required to position a single aerial image in space – easting, northing and height (real-world coordinates), and omega, phi and kappa (rotations around the X, Y and Z axes of the camera system).

Photogrammetry	The science of making accurate measurements from imagery, normally for the measurement of an object, mapping or geographic information system data collection.
Point cloud	A 3D visualisation constructed from millions of geo-referenced points.
Point density	A measure of LiDAR resolution, usually expressed in points per square metre (ppm^2).
Points of detail	Points that can be identified in both the terrain and in aerial imagery for the purpose of geo-referencing the imagery or for the determination of geometric accuracy.
Polar orbit	A satellite orbit that passes within 20° of both poles.
Position dilution of precision (PDOP)	A unitless scalar value expressing the relationship between the error in user position and the error in satellite position.
Precision	The degree to which a set of independent measurements match.
Pre-marked points	Points of detail that are established in the terrain before aerial imagery is captured.
Principal point	The position on the focal plane of a theoretically perfect camera where a perpendicular line passes through the perspective centre.
Push-broom scanner	A scanning action that uses a fixed linear array of detectors located at the focal plane to build up an image line by line along the direction of flight of the aerial platform. Push-broom scanners are also known as along-track scanners.
Radiometric	The measurement of radiant energy across the whole electromagnetic spectrum.
Receiver-independent exchange format (RINEX)	A common GNSS data file format.
Relative accuracy	The measurement of RMSE for normally distributed vector errors between approximate features shown in a survey or setting out on the ground. The calculation can be made independently of the absolute accuracy of features shown on a grid.
Relief displacement	The shift in an object's image position caused by its elevation above a particular datum. For vertical or near-vertical photography, the shift occurs radially from the nadir point.

Resolution	A measure of the level of detail that can be detected.
Root mean square error (RMSE)	The square root of the mean of the squares of the errors between the observations. It is a measure of the accuracy by comparing the actual measurements to the most likely value. In practical terms, this means that 95% (two σ) in a representative sample of points shall be correct to better than the stated accuracy value.
Short-wave infrared (SWIR)	Part of the electromagnetic spectrum.
Spectral signature	The variation in the electromagnetic reflectance from a homogeneous target.
Stereo photography	Pairs of photographs that can give a visual impression of depth, or a 3D representation.
Structure from motion (SfM)	A technique that uses a series of 2D images to reconstruct the 3D structure of a scene or object.
Sun-synchronous orbit	An orbit in which a satellite passes overhead at the same local time every day, tracking the sun.
Synthetic aperture radar	Synthetic aperture radar is an active microwave remote sensing technology that measures the phase difference between a radar wave emitted from an antenna attached to a satellite or an aircraft and its received echo from the terrain, to generate high-resolution images of the surface.
Tasked imagery	Earth observation imagery that is specifically targeted by the satellite imagery providers to meet the client's specific requirements.
Tidal window	A period when the coastal tides are at their lowest, usually twice a day.
Thermal imagery	Imagery created from detecting and recording the infrared part of the electromagnetic spectrum.
Unmanned aerial system (UAS)	This includes the ground control segment, the UAV and all equipment, network and personnel necessary to control the UAV.
Unmanned aerial vehicle (UAV)	Also known as a drone.
Virtual reference station (VRS)	A specialised processing technique that generates a virtual base station for a GNSS survey from a network of other fixed real base stations.

Whisk-broom scanner	Use of a rotating mirror to scan across the satellite's track or orbit, reflecting the energy emitted from the Earth's surface on to a single detector. The imagery is built up one pixel at a time. Whisk-broom scanners are also known as cross-track scanners.
Witness diagram	A diagram used to locate a point in the terrain, such as a ground control point.
World Geodetic System (1984) (WGS 84)	The geocentric datum used by GNSS since January 1984. It has its own reference ellipsoid.

Abbreviations

AGL	Above ground level
AOI	Area of interest
AQL	Acceptable quality limit
ATC	Air traffic control
BVLOS	Beyond visual line of sight
CIR	Colour–infrared photography; includes the near-infrared band
CMOS	Complementary metal oxide semiconductor
DSM	Digital surface model
DTM	Digital terrain model
ETRS89	European terrestrial reference system 1989
FOV	Field of view, usually expressed as an angle
FRZ	Flight-restricted zone
GCA	Ground control area
GCP	Ground control point
HAPS	High-altitude pseudo satellite
InSAR	Interferometric synthetic aperture radar
ISO	International Organization for Standardization
NIR	Near-infrared (part of the electromagnetic spectrum)
NDVI	Normalised difference vegetation index
PRF	Pulse repetition frequency, also known as pulse repetition rate (PRR)
RGB	Red, green and blue, or visible, imagery
RGBN	RGB and NIR imagery
RPAS	Remotely piloted aircraft system
SAR	Synthetic aperture radar
SfM	Structure from motion
SLAM	Simultaneous localisation and mapping

TDI	Time-delayed integration
TIN	Triangular irregular network, a representation of a continuous surface consisting of irregular triangular shapes
UTC	Coordinated universal time
VNIR	Visible near-infrared (part of the electromagnetic spectrum)
VTOL	Vertical take-off and landing

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