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# Application of the *Extended Ground Truth* Concept for Risk Anticipation Concerning Ecosystems



Antoine Gademer  
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## Abstract

Mapping is a fundamental tool in the study of ecosystems. It is usually done by field records, but this method consumes a lot of time and resources. Remote sensing is a complementary tool, but still needs ground-truth certification, due to the scale factor. In this article we present a concept, the *Extended Ground Truth*, which tries to keep the advantages of both mapping and remote-sensing techniques. The concept offers the use of imaging tools while providing a ground truth. We then develop this concept using one example concerning ecosystem analysis.

## 1. Introduction: Dynamic Cartography of Ecosystems

Mapping vegetation and its dynamics are major challenges for the study of ecosystems. Beyond the interest in fields such as forestry or agriculture, we place this article in the context of risk prevention: erosion, invasive spreading of weeds (plant species initially foreign to the environment where the species added itself [1]), health risks, etc.

### 1.1 Pest Plants

Indeed, among the plants brought by men from abroad, some have become invasive to a point where they gradually force the disappearance of the native vegetation, and form large homogeneous patches. These species are referred to as pest plants [2, 3]. These invasive species have several formidable qualities. They generally produce much fruit that is widely disseminated, by birds, small mammals, or, more rarely, by the wind, and they generally do not suffer from

parasites or pathogens. They form massive homogeneous patches that slow or block the forest dynamics, and they can also affect the herbaceous undergrowth. Colonization occurs mainly by taking advantage of an opening in the environment, whether natural or artificial. Once installed, by their ability of vegetative or sexual multiplication plant pests quickly become dominant over the natural vegetation, blocking any alternative process of native settlement. By the deep modification of the ecosystems (soils, flora, fauna, etc.) plant pests can thus provoke serious problems in many human activities (agriculture, fire, diseases, etc.), and cannot be put aside.

The risk management of biological invasions is difficult to conduct. Controlling illegal imports of plants is quite illusory. In addition, the behavior of newly imported plants is unpredictable, and the risk of having a new plague is greater than ever. To illustrate the importance of plant pests, we can take, for example, the case of Réunion Island. Réunion Island is particularly sensitive to biological invasions of plants and animals. The biological reasons are fundamental: isolated for millennia (about three million years), this island was not immediately settled by many species, as only a few of them have had the opportunity to move there, brought by air currents or by marine birds. Before the arrival of humans, the flora of Réunion was unique but fragile, and relatively poor. Exceptionally protected, Réunion was discovered and colonized by humans until the seventeenth century. Since that date, there have been many introductions, and no equilibrium has been established among the indigenous communities and invasive plants, with invasions taking place before our eyes. However, today it is generally accepted that 30% of the surface of the island (60,000 ha) is still covered with primary formations. The wild flora of Réunion is composed of about 650 flowering plants, native or endemic, and more than 450 exotic species, brought by humans since the seventeenth century.

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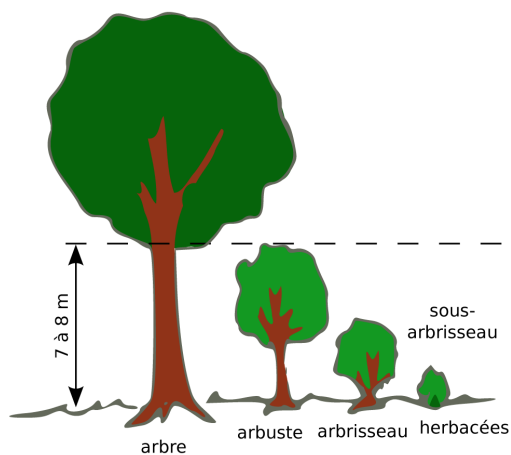


Figure 1. The scale distinctions between plants (source: Gademer).

The case of *Prosopis juliflora* is quite illustrative. It was deliberately imported in the 1920s [3] on the island of Réunion to reforest the lower slopes of the West Island, and for livestock feed. The plant has not fulfilled any of these functions. However, it quickly colonized much of the coastal plains, where it behaves as a dangerous invader.

Mapping is thus necessary to understand the complex interactions of plant species with each other, their environment, and the animal species. Mapping allows monitoring and anticipating the evolution of potential risk situations.

## 1.2 Plant Species Classification

### 1.2.1 Static Criteria and Constraints

Since the time of the great naturalists – such as Linnaeus and Buffon, who laid the foundations for the observation of species and their classification [4]—biologists



Figure 2a. An example of manual mapping methods: an ecologist forester measuring the diameter of trees near the Smithsonian Environmental Research Center (source: K. Bauer/SERC).

have attempted to clarify these classifications. They have done this through careful observation, based on the shape of individuals (popular classification), their properties (phenotypic classification), or, more recently, based on how they relate genetically (phylogenetic classification) [5].

Reliable species discrimination remains an important issue. Within an ecosystem, we can make a primary distinction based on scale. We speak of bushes for trees measuring up to 7-8 m high. Meanwhile, shrubs are perennials (a perennial plant has a life cycle that exceeds two years, as opposed to annual and biennial plants) and are branched from the base: they also have a small height. Unlike bushes, they do not have a distinct main trunk. Their multiple trunks are usually less than five centimeters big. For their part, herbaceous plants are defined in opposition to woody plants, such as trees or shrubs that produce wood. We show these distinctions in Figure 1.

Considering the small size and the high density of the last two representatives we have described above, the risk of misclassification is significant. This especially true since some species have very similar phenotypes, are closely intertwined with their parasites, or are overlapped with other plants that share their environment. All these criteria are constraints that make it difficult to distinguish species from each other.

### 1.2.2 Dynamic Criteria

To improve discrimination, this static view of species can be complemented by a dynamic vision of individuals within their ecosystems. Indeed, the study of the dynamics of the natural environment seeks to understand the interactions between species and their environment, as well as the evolution in time of these interactions. This requires relying on knowledge of taxonomy and physiology, as well as on knowledge of climatology, geology and pedology. It is then possible to rely on the phenological characteristics of plants, that is to say, the influence of the seasons and of



Figure 2b. An example of manual mapping methods: Soil coring by the members of the French National Museum of Natural History (source: B. Riera/CNRS-MNHN).



Figure 2c. An example of manual mapping methods: Measuring the linear profile of the ground height with a contact profilometer (source: weru.ksu.edu).

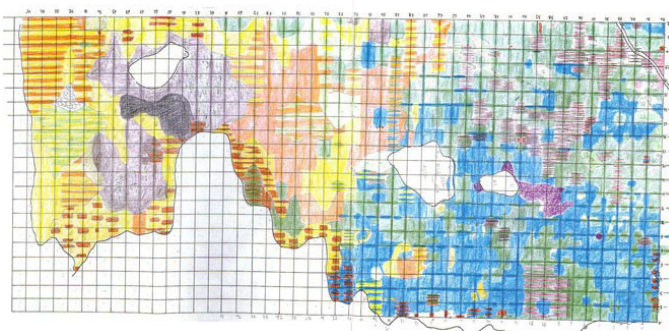


Figure 2d. An example of manual mapping methods: A map locating different phytogeographical groups (source: ONF [9]).

climate variations on plants' cyclical phenomena, such as germination or flowering. Some annual or biennials plants are visible only during part of the year, and in perennials, species looking similar stand out more clearly during flowering. Moreover, as they do not necessarily bloom at the same time, this reduces the risk of confusion.

The dynamic cartography of ecosystems is then a special task, which requires both accurate spatial tracking and a series of instantaneous temporal classifications, adapted to the lifestyle of individuals.

### 1.3 Mapping Methods of Plant Species

The dynamic evolution of ecosystems is studied by developing repeated land maps that incorporate spatial and temporal parameters of the classification. The location, the extent, the surface biophysical parameters (species, age, health, etc.) and geophysical parameters (soil type, moisture, exposure, etc.) of each group of individuals are identified and annotated. These maps are all representations of the state of the study area at the time of completion of the study.

Such studies, such as those described by Heller and Zavaleta [6], may extend over long periods of up to several decades. In botany, where the species usually have relatively long life expectancies (about 50 years for shrubs, a hundred years or more for trees), the periodicity of dynamic maps is of the order of three to ten years.

It should be noted that many species of weeds are annuals or biennials, and thus have much faster life cycles. We therefore note that in the context of risk prediction, it is necessary that the frequency mapping should be even higher than in the classical studies of ecosystems.

#### 1.3.1 Manual Mapping

In the absence of an alternative technique to grasp this field truth, the dynamic mapping of the living is often

done manually, via the annotation of paper charts by a small team of researchers and students (see Figure 2).

As we quickly found out with the botanists of the French National Museum of Natural History (MNHN) (Tropical ecology, UMR 7179, Ecology and Management of Biodiversity Department, CNRS – MNHN), this manual mapping involves tedious logistics. Both human and financial costs rapidly become a limiting factor for the quality and quantity of observations. The scope of the work of analysis and interpretation is therefore reduced, despite the use of statistical techniques and the definition of a representative sample of study sites.

In addition, a sub-meter mapping of a few acres can last several months: the surfaces of the study areas covered are therefore often small. For example, it takes about five weeks for an MNHN team of two botanists to cover two hectares of their study area. Under these conditions, any limitation of resources quickly results in reducing the mapped area, thereby penalizing the statistical quality of the final study.

This extended period of transcription spent in the field is the cause of other problems. First, the accuracy of mapping is affected: the time required for the description of each individual is prohibitive. Botanists then define phytogeographical groups – relatively homogeneous – which they spatially characterize with an accuracy of about 20 cm. These groups are approximations of floristic characteristics of individuals: for example, “*Calluna vulgaris* plants that measure less than 40 cm.” However, they do not consider the possible mixing of species within a group, the density of individuals, their specific age, or their state of health.

However, this also raises the reliability of the classification. We discussed the possibility of relying on the phenological characteristics of species to improve the distinction, but this advantage can turn into a disadvantage because of the long mapping period: in a month of work, the same phenological phenomena can change the appearance of plants, and then disturb the viewer. To this must be added the fact that manual mapping is subject to a strong



Figure 3a. An image acquired by aerial remote sensing.

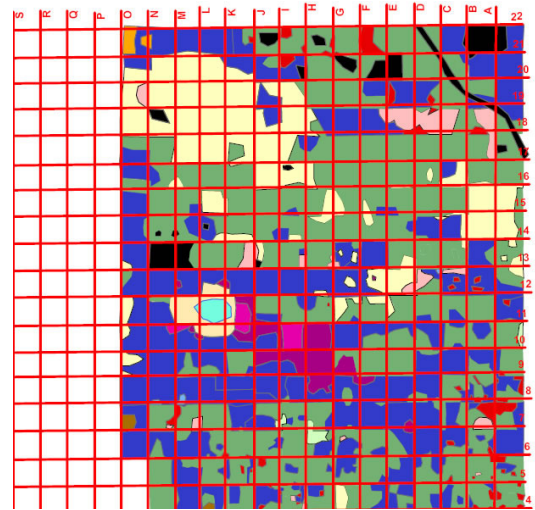


Figure 3b. An example of a map created from the image of Figure 3a.

subjective bias. This increases the degree of uncertainty in the data when comparing maps of the same area of study, made without consultation by different observers. It should also be noted that for lack of sufficient statistical visibility, species underrepresented and/or short-lived cannot be integrated into the mapping at the expense of the analysis of the entire ecosystem.

It is noteworthy that the manual mapping of phytogeographical groups is meticulous work, which must adapt to the natural cycles of species we seek to identify. If a floristic approach, based on individuals, would be much richer and more interesting for botanists, it is often unattainable, given the current resources at their disposal.

### 1.3.2 Remote-Sensing Mapping

Another way to achieve these maps is to use advanced imaging techniques (see Figure 3). Indeed, we have seen significant benefits in monitoring the dynamics of ecosystems through the use of remote sensing [7]. In the article of Lu [8], we saw more specifically the potential of remote sensing for the assessment of plant biomass above the ground, that is, all the living resources (trees, shrubs, plants, etc.) in a given space.

Remote sensing offers the opportunity for mapping out faster than manual mapping. It thus allows considering several observations of the phenological cycle (flowering, leafing, leaf coloration, etc.) at different times, offering at the same time a much better identification or differentiation of individuals: if calluna and heather are difficult to distinguish with the naked eye, they do not have the same flower or the same time of flowering. Two observations at two epochs carefully chosen may allow easy differentiation, and the identification of certain short-cycle plants (visible only for a few months, such as the crucifers of the rumex acetosella).

It must be said that the limits of this system are generally a mismatch between the scale of measurement in the field and the level of the acquired images. If spatial remote sensing allows observation over large spatial and temporal scales, it generally lacks precision for understanding the complex phenomena involved. It is then usually necessary to certify the data by field surveys: what we commonly call *ground truth*. We can cite the work of [9] and [10], which sought to establish a relationship between the local measurements obtained during field surveys, and characteristics (spectral signature, texture, or volume) of the data acquired by satellites, in order to extrapolate this relationship to the study of much larger areas.

Another critical point concerns the accuracy of the mapping. Indeed, if forest maps can rely in part on aerial or satellite imagery [9, 10], mapping of shrubs and herbaceous plants can usually only be done by manual annotation during field surveys. It is understood that the small size of these plants – between 20 cm and 1 m – and their high density and degree of entanglement do not allow conventional approaches based on the interpretation of remote-sensing images, which are used to count trees.

## 2. The Extended Ground Truth Concept

In the previous section, we have seen the need for a new concept, incorporating potential benefits of both imaging and field-survey methods. This new concept would significantly improve the extraction of biophysical and geophysical surface parameters in field missions. For this to work, it is necessary to work with data (images) at the scale of individuals.

Our new concept, Extended Ground Truth, can be stated as a methodology for ground-truth data acquisition

Feature	Land records	Classical Remote Sensing
Source of analysis	Instant and volatile	<b>Perennial images</b>
Repeatability	Subjective bias	<b>Systematization possible</b>
Method of measurement	Manual	<b>Automated</b>
Mission time	Limited by the human factor	<b>Extended by the possibility of delayed analysis</b>
Schedule	<b>Adapted to the phenology of species</b>	Determined by orbital or administrative constraints
Measures	<b>Direct measurements (size, color, etc.)</b>	Estimated based on the properties of the sensor
Certitude	<b>Ground truth</b>	Interpretation of a signal

Table 1. A comparison of the features of land surveys and classical remote-sensing techniques. In bold, the characteristics we want to keep in Extended Ground Truth.

of biophysical and geophysical parameters at the level of individuals, using advanced imaging techniques.

## 2.1 What Features to Keep Between Those of Land Records and Those of Classical Remote Sensing?

We examined which features of the two techniques – classical remote sensing and land records – it would be desirable to keep for performing remote sensing at the scale of individuals. These are described in the following sections, and summarized in Table 1.

### 2.1.1 Durability of Images

In a field survey, information analysis is made on-site, and only the land-cover mapping is carried out. It is therefore no longer possible to retrospectively reanalyze the data sources in the light of new information. With remote sensing, we acquire source images corresponding to a “snapshot” of the scene at a given time, and we then analyze the images to extract the land-cover map. Being able to keep the source images of a study for another study permits reanalyzing them given additional information. Furthermore, if they are geometrically rectified, the source images are stackable. This allows an easier comparison of the dynamic changes from one period to another. With Extended Ground Truth, we want to keep this property. We want to produce images of comparable sources that can be analyzed at leisure, to extract information from the highest level (as surface parameters) of interest to botanists.

### 2.1.2 Repeatability

The great difficulty in field surveys is to produce homogeneous information. Indeed, the observation conditions change during the mapping (light, tiredness, etc.), or from one study to another (not the same person,

not exactly the same instructions, etc.). When working as a team, botanists locate the data each time in an absolute and identical reference, based on a decametric grid positioned using GPS, and allowing a comparison study. However, if another team needs to choose another reading grid, data comparison can be problematic.

Nowadays, the use of photography in land records is not subject to any shooting constraint (generally, oblique photographs are taken by hand, showing the global situation), and photographs are therefore difficult to compare. In remote sensing, the intrinsic rigidity of the images allows stacking the images acquired in different studies, when they are rectified in geometry and acquired at consistent scales. This capability of the repeatability of the acquisition in almost identical conditions is an important advantage of remote sensing, and we seek to keep it when measuring in Extended Ground Truth.

### 2.1.3 Automatic Analysis

Due to the high repeatability of the acquisition of source images, the conditions of the extraction of the parameters of surfaces are generally similar. The processing of remote-sensing images has become increasingly automated (segmentation, calculation of indices or surface parameters, classification, etc.). Based on imaging, the Extended Ground Truth concept is obviously trying to tap into this arsenal, to give researchers in the field the best tools for their studies.

### 2.1.4 Mission Time

In addition, we note another methodological change: during land records, the interpretation of the information is performed on-site in the form of paper maps and GPS readings. The information is then digitized in the laboratory. In contrast, the use of imagery allows the digitization of information directly on the ground, and later analysis in the laboratory. As the longest work is generally the analysis, by

allowing later analysis Extended Ground Truth can enable devoting precious time spent in the field to the point. This allows us to study a larger area, or to repeat the acquisition more often (for example, at both morning and evening, which allows the use of other phenological properties), or to reduce costs.

### 2.1.5 Acquisition Schedule

On the other hand, conventional remote sensing is not a panacea for mapping at the scale of individuals. Gigantic sensors, sometimes located thousands of miles away, are used. They are subject to external constraints (orbital or aerial constraints, cloud cover, etc.), which can be extremely demanding. By definition, a sun-synchronous satellite can never take pictures at a different time than that for which it was provided, and the period between two acquisitions is limited by the satellite's time revisit of the site.

The use of an air carrier (airplane, microlight, etc.) offers greater flexibility than satellite imagery, although traffic in the airspace itself is highly regulated (flight plan, need for an aerodrome and a driver, etc.). However, the main obstacle to the use of airborne imagery is its cost (usually between five and 10 times that of the satellite's).

To find intermediary acquisition vectors that enable both operational flexibility and a reasonable cost, we must turn to extremely-low-altitude remote-sensing tools. These are usually flying machines, robotic or otherwise, which do not exceed a ceiling of 150 m, but allow photographic material as their payload: kites, balloons, aircraft models (manned), or drones (automated). Because of their versatile features and their ability to be directly used from the field study, these tools are close allies of Extended Ground Truth.

### 2.1.6 Direct Measurements of Characteristics

Remote-sensing analysis, unlike land surveys, does not provide direct measures of individual characteristics, but these measures are inferred from the interpretation of source images. To extract dendrological phenotypic parameters, it is essential to have a complete and sufficiently precise view of individuals. Most of the time, this is not possible with conventional remote sensing. However, with the use of extremely-low-altitude remote-sensing tools, Extended Ground Truth allows high-resolution mapping at the scale of individuals, and thus allows the extraction of these parameters.

### 2.1.7 Certification

Using imagery to perform ground truth is a big gamble. By definition, remote sensing is indeed a science of interpretation of the physical properties (optical, roughness,

etc.) of objects to determine their nature. This is why remote-sensing studies are usually doubled by field studies to define a punctual ground truth, giving a confidence indicator on the analysis carried out by remote sensing. In the case of Extended Ground Truth, the initial idea is to expand opportunities for land records. We therefore had to find a way to abstract this constraint. How can the opportunity be given for experts to certify the results automatically obtained by means of Extended Ground Truth? The answer is by acquiring the images of sources at a scale where visual interpretation is unquestionable, in other words, by taking the images at the scale of the individuals.

## 2.2 What is New with Extended Ground Truth?

The idea of using images acquired at a smaller scale to serve as ground truth is not new. In fact, [11] showed the interest of photographs taken by hand from a small plane for the interpretation of optical and radar images acquired by satellites. However, if these oblique images allowed the confirmation of their assumptions, they do not allow them to retrieve surface parameters. In addition, no shooting constraint was determined for the acquired images, and these were not used for the production of maps, but only as ground truth. In their case, [12] used low-altitude remote-sensing tools, such as hang gliders and helium balloons, with the same goal. However, again, the images were not sufficiently accurate to be used beyond visual interpretation. These examples are typical of the role previously reserved for imaging in land records.

In a complementary approach, [13] proposed the development of a tool allowing the acquisition of spectral responses from the vegetation to serve as a formalized ground truth for satellite images. Their sensor was carried by a truck crane, so it did not meet the desired criterion of operational flexibility. However, these studies showed the need and the possibilities offered by high-resolution data acquired on the ground for the analysis of results on a larger scale obtained by satellite remote sensing.

The work in [14] and [15] (tethered balloon), [16, 17] (airships), [18] (kites), [19] (automated paragliding), [20] (controlled model airplane), [21] (automated aircraft), [22] (controlled model helicopter), and [23] (automated helicopter) showed spectacular advances in recent years in remote sensing at low altitude. These tools provided a mapping with millimeter or centimeter accuracy, and were therefore ideally suited to mapping at the scale of individuals. However, apart from work in precision agriculture, it is unusual to consider plants smaller than trees at the scale of individuals, and to take into account their biophysical characteristics. This is why we propose a formalization of the concept of Extended Ground Truth that seems to be a promising lead for research on extracting biophysical and geophysical surface parameters in general, and for vegetation mapping at the scale of individuals, in particular.

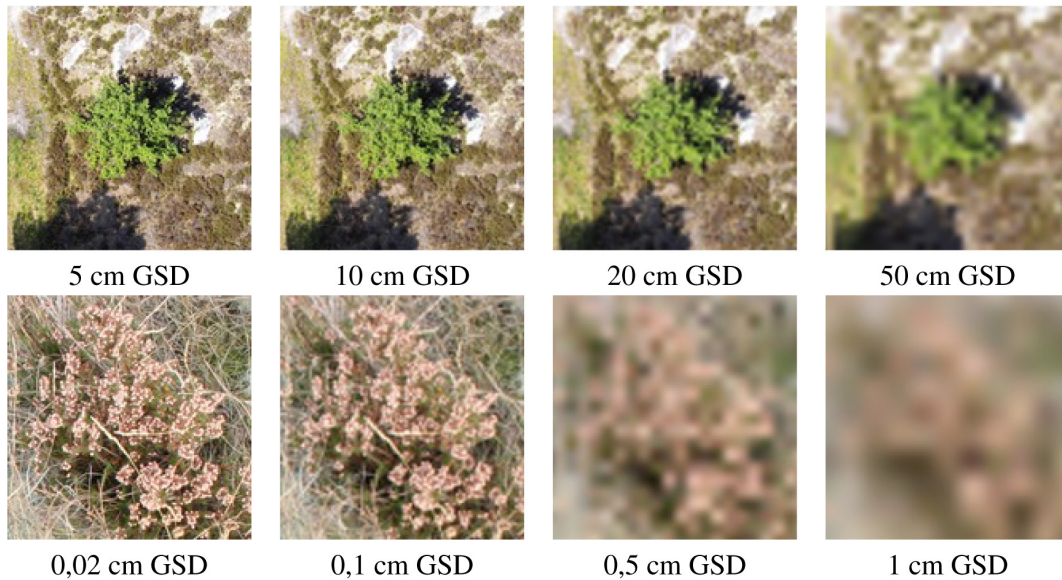


Figure 4. Examples of simulated images of two scenes. The size of the GSD varied during the acquisition, although it is displayed on the same scale. We see that the sample size, which corresponds to the area on the ground for a photo site, determines the size of the smallest identifiable object in the image.

## 2.3 The Extended Ground Truth Methodology

To produce Extended Ground Truth, it is necessary to take into account a number of technical constraints. In this section, we formalize the concept and describe the different stages of the feasibility study, in order to be able to take images that meet the criteria.

### 2.3.1 Determining the Size of the Ground-Sample Distance

In order to map at the scale of individuals, we must begin by questioning the size of the individuals we want to observe in the study area. This allows us to define the size of the ground-sample distance (*GSD*, in millimeters) needed for mapping. As we can see in Figure 4, we consider the smallest identifiable object on an image corresponding to a given *GSD* as having a size of about five to 10 times the size of the *GSD*. For example, if we wish to observe mangroves the crown of which is about 30-50 cm in diameter, we need a *GSD* from 50 mm (the limit of distinction: this size allows distinguishing objects with a size of at least 25-50 cm) to 10 mm (very detailed: this size allows distinguishing objects with a size of at least 5-10 cm). If we want to observe the flowers or leaves on the crown, we may consider a more specific *GSD* of 1 mm, for example.

Once we have fixed the interval, the choice of the *GSD* depends of the analysis we want to achieve. This will require more or less detailed views (density evaluation, delineation of parcels, etc.). The choice of the *GSD* also depends on other feasibility constraints that we address in the

following sections. For the remainder of the study, we will do the calculations for several typical values of this interval.

### 2.3.2 Determining the Type of Sensor

It is next necessary to choose the type of sensor that can meet the needs of the mission. The choices are numerous: compact digital or reflex camera, aerial camera, LIDAR, etc. The type of sensor itself (camera, video camera, etc.) depends in particular on the needs for the analysis, and on constraints such as weight and size (the throw weight of the carrier, as we will see later), cost and availability, etc. However, some of the most important criteria in the feasibility study correspond to the optical properties of the sensor. We are mainly interested in maximum exposure time, pixel resolution, width of the optical chamber, and focal length.

#### 2.3.2.1 Estimating the Maximum Flight Speed According to the Constraints of the Sensor

The maximum exposure time of the sensor ( $TimeExp_s$ , in seconds) will constrain the flight speed to avoid motion blur in the shooting (Figure 5). For a given *GSD* ( $GSD_{min}$ , in millimeters), the maximum flight speed ( $vmax_{mm/s}$ , in millimeters per second) is given by Equation (1):

$$vmax_{mm/s} < \frac{GSD_{mm}}{2TimeExp_s}. \quad (1)$$



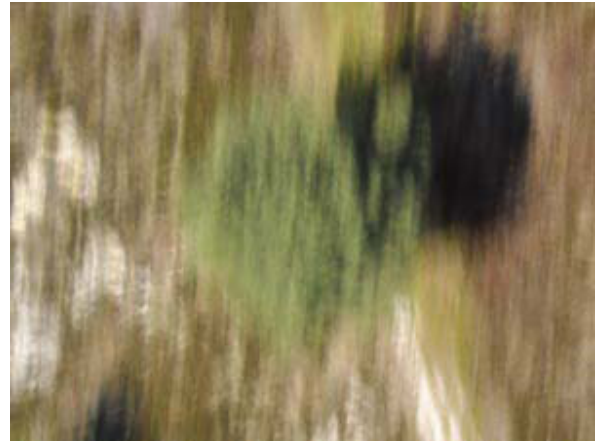


Figure 5. (a) An image without motion blur, and (b) an image with motion blur.

We consider that the carrier should not move more than half of a pixel during the acquisition (an empirical estimation validated by our experiments). Note that the exposure time depends on the lighting conditions, and on the aperture of the device.

### 2.3.2.2 Estimating the Necessary Flight Height According to the Constraints of the Sensor

The resolution ( $R_{pix}$ , in pixels), the width of the optical chamber ( $L_{mm}$ , in millimeters), and the focal length ( $f_{mm}$ , in millimeters) allow us to determine the flight height ( $H_{mm}$ , in millimeters) needed to obtain the desired GSD ( $GSD_{mm}$ , in millimeters) (Figure 6). This is given by Equation (2):

$$GSD_{mm} = \frac{L_{mm}}{R_{pix} f_{mm}} H_{mm} \Leftrightarrow H_{mm} = \frac{R_{pix} f_{mm}}{L_{mm}} GSD_{mm} . \quad (2)$$

### 2.3.2.3 Estimating the Scan Swath According to the Constraints of the Sensor

The resolution of the sensor ( $R_{pix}$ , in pixels) will allow us to calculate the total width of the surface seen on an image, called the scan swath ( $F_{mm}$ , in millimeters). For a given GSD ( $GSD_{mm}$ , in millimeters), we have

$$F_{mm} = R_{pix} GSD_{mm} . \quad (3)$$

We will use this to estimate the maximum time we should have between two shots, and also the time of over-flight of the area.

### 2.3.2.4 Estimating the Overlap Rate Between Two Shots According to the Constraints of the Sensor

From the scan swath ( $F_{mm}$ , in millimeters), we can estimate the base ( $B_{mm}$ , in millimeters) that corresponds to the distance between two shots (Figure 7). This value will constrain the overlap rate ( $r_{prct}$ , percent expressed as a fraction), an important parameter for image mosaicing (which needs an overlap of about 30%), or to create stereo pairs (which needs an overlap of about 60%). This information is grouped into Equation (4):

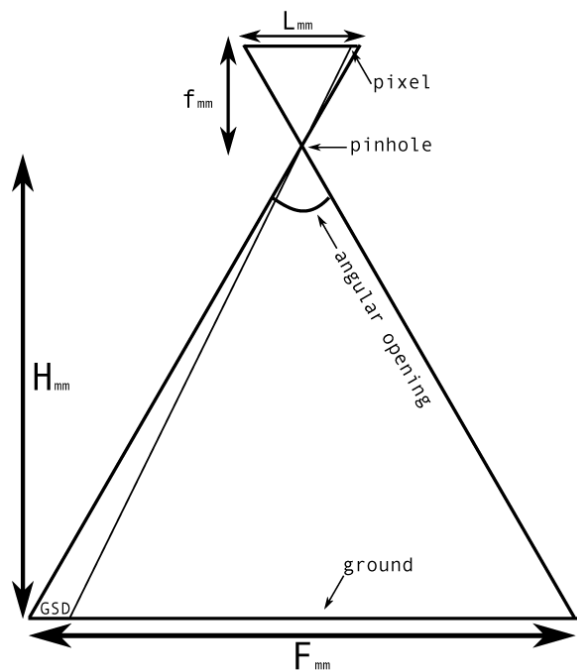


Figure 6. An illustration of the relationships among the scan swath (or the GSD), the parameters of the sensor, and the height of flight.

### 2.3.3 Determining the Type of Carrier

Constraints obtained from the sensor will help determine the choice of the carrier, in terms of the throw weight, the speed of flight, as well as the flying height. If the carrier does not meet these constraints, we must find another one that fits best, look for another sensor, or review the requirements about the *GSD* until we find a satisfactory solution.

### 2.3.4 Validation of the Choices: Time and Cost of the Mission

Finally, we estimate the coverage and therefore the required flyby time to complete the mission, and therefore its cost.

For the case of a rectangular area with a width less than the width of the scan swath ( $l_m < F_m$ , in meters) and a length ( $d_m$ , in meters), and given the speed of flight ( $v_{m/s}$ , in meters per second), the time ( $t_s$ , in seconds) to map this area is given by the classical formula

$$t_s = \frac{d_m}{v_{m/s}} \quad (7)$$

However, if the area is larger than the width of the scan swath, the overlap rate must be taken into account. For example, if the width of the over-flown area is twice the width of the scan swath, it will take three flybys, and thus about three times the time calculated with the above formula (Figure 8). If we denote the width of the area by  $l_m$ , the scan swath by  $F_m$ , and the needed overlap rate by  $r_{prct}$ , we can deduce the following formula from Equation (7):

$$t_s \cong \frac{d_m \left[ \frac{l_m}{F_m} (1 + r_{prct}) \right]}{v_{m/s}} \quad (8)$$

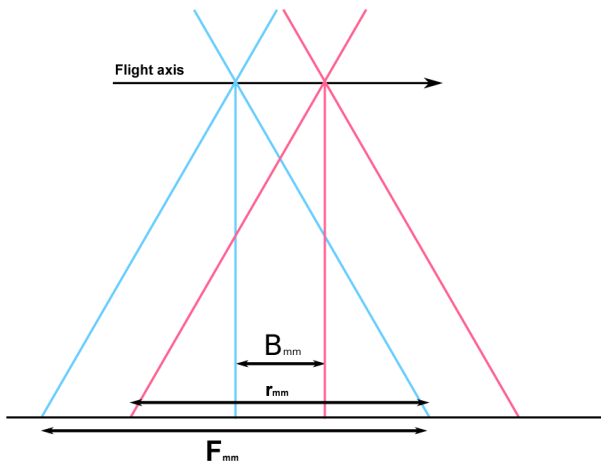


Figure 7. An illustration of the relationships among the scan swath, the base, and the overlap rate.

$$B_{mm} = F_{mm} (1 - r_{prct}) \quad (4)$$

According to Equation (3), we thus obtain

$$B_{mm} = R_{pix} GSD_{mm} (1 - r_{prct}) \quad (5)$$

Once the speed of flight is set, this will tell us the maximum time ( $t_{max_s}$ , in seconds) between two shots required in order to get the desired overlap rate. It is necessary to check that the sensor is able to perform two consecutive shots in this period.

$$t_{max_s} = \frac{B_{mm}}{v_{max_{mm/s}}} \quad (6)$$

$$= \frac{R_{pix} GSD_{mm} (1 - r_{prct})}{v_{max_{mm/s}}}$$

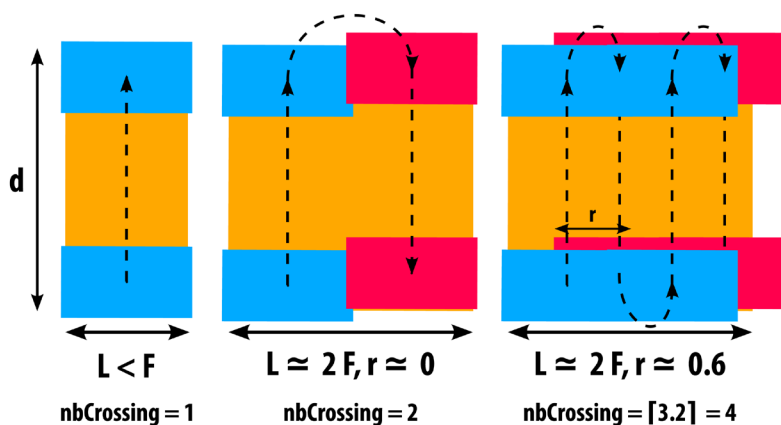


Figure 8. An illustration of the calculation of the flyby time based on the overlap rate.

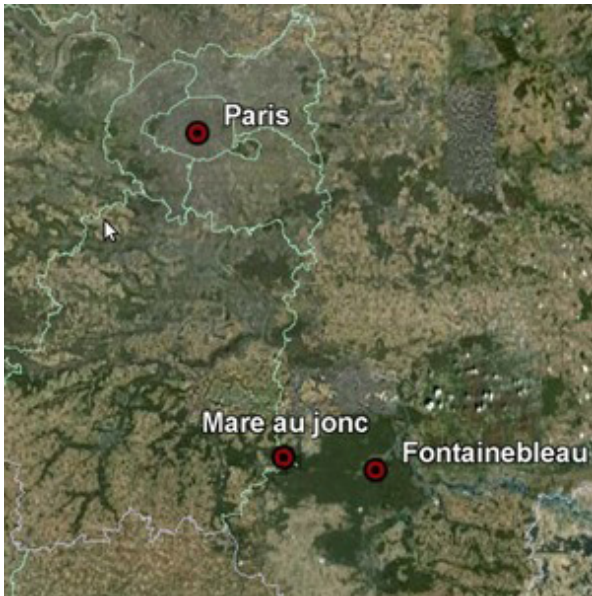


Figure 9a. The location of the Mare aux Joncs area (source: Google Maps).



Figure 9b. What surrounds the Mare aux Joncs area (the study area is delimited by the red frame) (source: Google Maps).



Figure 9c. The study area (source: Google Maps).

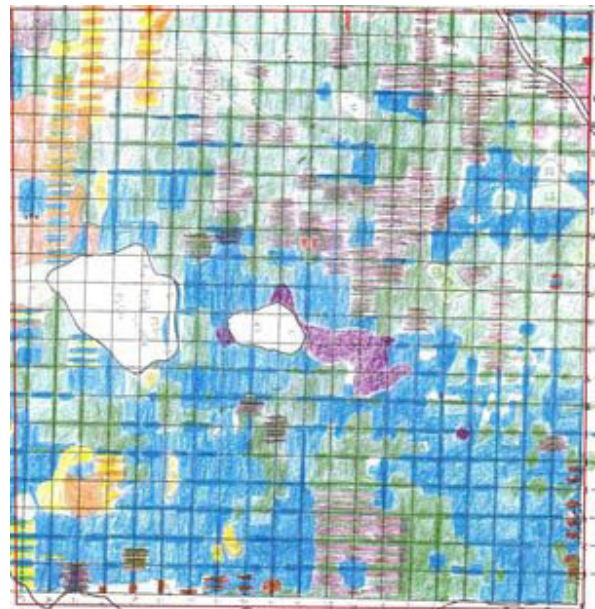


Figure 9d. A manual map of the study area (source: ONF).

The ceiling in the numerator corresponds to the fact that the number of passages (calculated from the width of the area, the width of the scan swath, and the overlap rate) is necessarily an integer (no halfway is possible). In the case of a rectangular field, we will consider the bounding rectangle.

We could add that the calculated time is a minimum time. We must account for the time required for flipping the carrier, and for performing the passages to reinforce the geometric constraints (perpendicular to the previous flights). We also have to take into consideration the constraints of autonomy, and the time to return to the ground station to change batteries.

Again, if the result is not satisfactory, we must return to the previous step and adjust the settings accordingly.

### 2.3.5 General Remarks

The process of selecting the sensors and carrier adapted to each mission is an iterative process. It seeks to minimize the various constraints of low-altitude remote sensing (the theoretical constraints, such as those we just developed, as well as constraints of feasibility, costs, or availability, etc.). Our experience shows that there is no single solution applicable in all circumstances, but there is a methodology to roll out whenever necessary.

### 3. A Study Case: The Trois-Pignons Forest Area

In the context of this article, we present our collaboration with a team from the French National Museum of Natural History (Tropical Ecology, UMR 7179, Ecology and Management of Biodiversity Department, CNRS – MNHN). The objective was to study the evolution of the dynamics of vegetation on the Mare aux Jones test area, located in the Trois-Pignons forest (France, see Figure 9). This area of four hectares stands on the boundary between heath-land and forest. It is mainly populated by shrubs (< 80 cm) and grasses, as well as isolated trees producing shoots.

Until this study, the mapping of this area was mainly conducted by manual land records, complemented by aerial ortho-images provided by the French National Institute for Geographic Information and Forestry (IGN). The aim of our work was to validate the interest of low-altitude acquisitions to obtain Extended Ground Truth.

To acquire the data, we needed an acquisition system composed of a carrier and optical sensors. Based on the presented methodology, we will see the reasoning that led us to the following choices: a micro-quadcopter, allowing stationary or slow flight, with a payload capacity of the order of kilograms, to be able to carry one or more sensor devices, such as cameras. We will describe this system in more detail in the following sections.



Figure 10a The Faucon Noir UAS.



Figure 10b. The Faucon Noir UAS in flight.

### 3.1 The Low-Altitude Remote Sensing Tool: Faucon Noir, a Light Homemade UAS for Centimetric Mapping

#### 3.1.1 Choice of the System

In their manual mapping, the botanists of the French National Museum of Natural History consider only individuals greater than 10 cm in diameter. However, formal identification of the species of these individuals requires recognizing structural elements of only a few centimeters. We therefore estimated *a priori* that we needed a *GSD* better than 1 cm. Considering an average brightness and a standard diaphragm aperture, we set the exposure time to between 1/400 s to 1/800 s. Equation (1) gave us a maximum flight speed of the order of 7 km/h to 15 km/h, which eliminated most of the fixed-wing carriers that required a higher speed to sustain flight. Moreover, the desire of an important maneuverability to cover the whole study area in a semi-automatic mode, and the need for a strong resistance to wind gusts – up to 25 km/h in the area – eliminated carriers such as kites and balloons.

That left the vertical takeoff and landing (VTOL) vehicles: carriers such as helicopters (with a main rotor and a variable pitch), or multi-rotor aircraft (with multiple rotors and a fixed pitch). The VTOL carrier had the advantage of performing stationary flight or, with a speed as slow as you want, possessed a great maneuverability. They were easy to deploy (since they did not require a landing strip), but they generally have a limited endurance (they consume a lot of power to keep themselves in the air).

Although the carrying capacity of VTOL carriers does not reach the capacity of fixed-wing carriers or of tethered carriers, multi-rotors are distinguished from helicopters by their increased capacity to carry material. That made them very attractive to us. Moreover, with their short propellers, they were easier and safer to handle. However, unlike helicopters, which provide mechanical stability with the



Figure 10c. The Faucon Noir UAS in flight, equipped with one of its mapping payloads.

Size (without landing gear)	70×70×15 cm + 35 cm with landing gear
Weight (with batteries)	1.6 kg
Maximum weight available for payload	1 kg
Battery	Lithium Polymer 11.1 V 8400 mAh
Maximum power	1 kW
Endurance (no payload)	25 minutes
Endurance (with payload)	20 minutes
Frequency control	72 MHz
Frequency ground station	2.5 GHz
Maximum height (visual flight rule)	80 m
Maximum height (automatic mode)	150 m

Table 2. Main characteristics of our Faucon Noir UAS.

flybar and their long propellers, multi-rotors carriers are inherently unstable, which is generally offset by an active electronic control.

### 3.1.2 Our System

At the time of this study, there were not many multi-rotor systems commercially available, and none allowed carrying 1 kg of material. We therefore built our own prototype to meet the aforementioned constraints: a quad-rotor carrier (Figure 10), called Faucon Noir [24]. As usual for autonomous robotics, the system architecture was quite complex. There was a low-level assistant board (based on a real-time microcontroller chip) that ensured sustaining flight and communication with the pilot. There was a high-level computer that did the complex navigation, based on GPS data, and was also used as a flight-data recorder.

The low-level assistant was critical, as it controlled the attitude and motion of the UAV in real time and at high frequencies. It was developed with the greatest care. A malfunction of this card always meant a serious accident. Developed as flexible systems, other boards could be plugged in to add important functionalities, such as altitude control or full payload control (acquisition, orientation, and data recording). At the time of the study, our prototype had only an attitude control, a full payload

control, and an altitude-measuring unit. It achieved only the minimal requirements for the mission. Nowadays, full attitude, altitude, and position controls are available on most commercial multi-rotor unmanned aircraft system (UAS) at a reasonable cost, strengthening the operational capacity of these tools. The flying robot was completed by a set of software tools running on the ground-station computer. This software allowed real-time checking of the state of the machine, provided a visual check of what was seen from the onboard cameras, and allowed acquisition control. The main characteristics of our Faucon Noir UAS are summarized in Table 2.

## 3.2 The Mapping Payload

### 3.2.1 The Choice of the Sensors

Considering the flight speed of our device, the *GSD* of 1 cm maximum we chose imposed a shooting period within six seconds (minimum speed), and three seconds (maximal speed) for an overlap rate to perform stereo-restitution (60%). This constraint was achievable for most commercial digital cameras. On the other hand, from an operational point of view, the instability of platforms such as a micro-unmanned aerial system make the reliability of

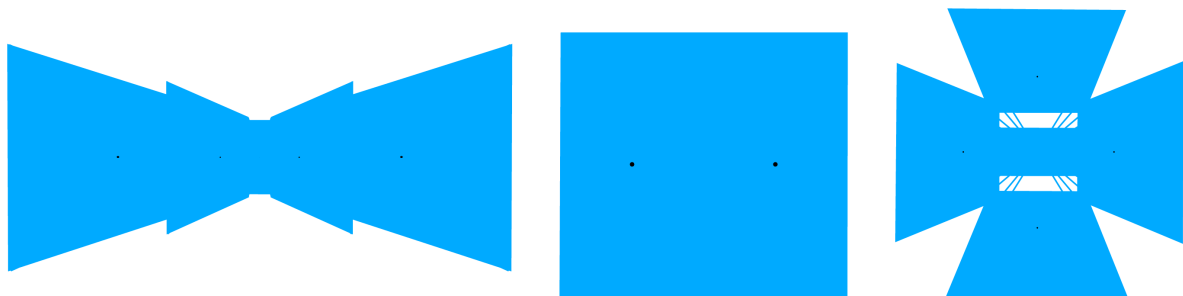


Figure 11. Representations of the scan swath for the three types of multi-camera systems cited: (l) the “fans” type; (c) the “block” type; (r) the “Maltese-cross” type.

the overlap rate difficult. We therefore decided to develop a dedicated mapping payload. Equipped with multiple cameras, it allowed simultaneously taking shots, and thus ensured obtaining synchronized stereo pairs.

We can distinguish three types of multiple-camera systems [25] (Figure 11):

- The “fans” systems, which include several cameras aligned perpendicular to the axis of flight. They thus have strong incidence angles, and therefore strong geometrical deformations.
- The “block” systems, combining cameras having very low incidence angles, thus having little deformation.
- The “Maltese-cross” systems, consisting of a vertical camera surrounded by several oblique cameras. This type of system is particularly desirable for defense and security applications [26], as well as for mapping land use [27], due to the ease of visual photo interpretation of oblique images.

Our payload consisted of three devices aligned along the line of flight. The orientation of the front and rear cameras was adjustable in flight. This allowed us to get the “Maltese-cross” or “block” types of configurations, according to the needs of the mission (Figure 12).

The camera must have good image quality and support manual settings, while remaining as small and light as possible. References [28-30] showed that the quality of images produced by non-professional digital cameras was satisfactory for remote-sensing applications. Optical distortion due to non-professional lenses can be considered acceptable with fixed lens systems if one takes the trouble to perform a calibration before the flight. We chose three compact digital cameras weighing less than 200 g, thereby complying with the constraint of a payload less than 1 kg.

### 3.2.2 The Control of the Payload

Controlling a camera covers operations such as switching on, triggering the acquisition, and, in our case, dating and validating the shots. Another point for geo-

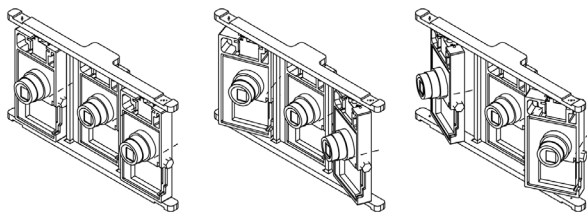


Figure 12a. Our tri-camera system: an illustration of the possible orientations of the cameras inside the system.

localizing the data concerns the synchronization of shots between the devices themselves, and with the other sensors of the system. This was all the more important in that quadrotor carriers can very quickly change position.

Generally, commercially available systems only deal with the triggering: the devices must be switched on manually, and users must settle for the dating inside the unit. The automated triggering systems that existed at the time of our study (mechanical, IR, etc.) did not meet our criteria. In our tests with an infrared remote control, we realized that the frequency of shooting was very low, the timing was unfortunate, and the order of shooting could be ignored if the camera was not ready. We thus chose a solution that was intrusive. We connected a homemade control card directly to the internal electronics of the camera. Our control card used the ability of a microcontroller to relay, analyze the signals from the device, and communicate with the rest of the system. It electronically triggered simultaneous shots and dated them when the acquisition signal was issued, all with an accuracy of about 20 milliseconds. The digital camera then became a fully controllable device.

### 3.3 Data Acquired and Results

Several hundreds of pictures were acquired with the system over the Mare aux Jones study area. Many of them were blurred, due to the strong wind and the fact that our unmanned aircraft system was still under development at the time of the mission. The scale constraint was also a difficult goal to achieve with a quadri-copter without automatic height control (as can be found nowadays in most rotary or fixed wing unmanned aircraft systems). The automatic processing of the data was thus not feasible at that time. For the same reason, the 1 cm GSD constraint was not obtained for the whole sequence. Nevertheless, an automatic mosaicing algorithm was applied to a subset of the data with good results (Figure 13). This produced perfectly usable land-cover maps (geolocated orthoimages stackable on maps) for the identification of species.

Manual cartography was done during the test campaign. A second cartography was produced based on the sole observation of the image data, to allow comparison of the efficiency of the Extended Ground Truth methodology.



Figure 12b. The tri-camera system as built.



Figure 13a. A mosaic of the stackable orthoimages acquired for the area.



Figure 13b. An enlargement of the upper-right-hand corner of the mosaic shown in Figure 13a.

Reference [31] showed that compared to classical airplane images, the images acquired with a 5 cm *GSD* allowed the identification of trees, bushes, shrubs, and herbaceous plants. However, it was still not sufficient for close relative species of shrubs (indicating the need for lower acquisition) with a precision similar to manual cartography. The PhD thesis of the author of [31] concluded with strong interest in this method for ecosystem studies and general biodiversity management.

On our side, this test mission gave us satisfying elements showing that Extended Ground Truth had a concrete interest to enlarge the scope of field records. Obviously, a more reliable version of our unmanned aircraft system would allow us to perform better data acquisition, and to develop the full potential of automating the process. From an operational point of view, making several acquisitions of the same scene at different scales (1 cm *GSD* and 10 cm *GSD*, for example) could allow a stronger geo-localization of the images.

The oblique images produced (Maltese-cross mode) were used for visual interpretation (Figure 14). The stereo images (block mode) were used in the PhD thesis of [32] (Figure 15). This proved the feasibility of automatic extraction of the surface parameters (Figure 16), as ground roughness or dendrometric parameters, with low-altitude stereo couples.



Figure 14. A mosaic created with the oblique images.

## 4. Conclusion

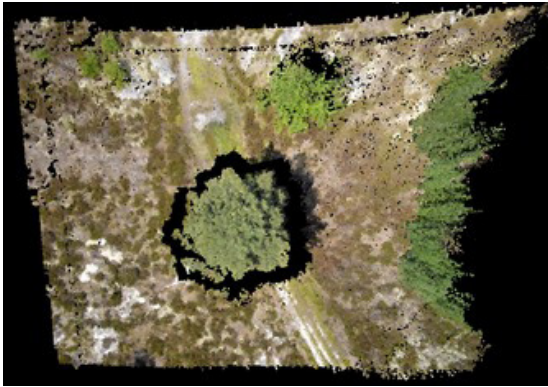
In this article, we have presented the concept of *Extended Ground Truth*, which allows using the efficient tools of imagery while preserving the certification of the data (ground truth) usually provided by land records. To obtain data compatible with Extended Ground Truth, we developed the methodology that allows fixing technical choices according to the mission criteria. We have seen that this process is iterative, and that there is no universal solution.

We used this methodology to map ecosystems at the level of individuals in the study area of the Mare aux Jones, with an acquisition system we developed. One of the background objectives of this study was to survey the invasion of the forest on the moor, a characteristic and thus protected area of the region. According to experts, the first results we obtained were very encouraging. We showed that the Extended Ground Truth methodology and the tools we used offer the possibility for precisely distinguishing plant species, even if they are very small. They thus make it possible to classify and produce precise and stackable maps, which could be reanalyzed at leisure.

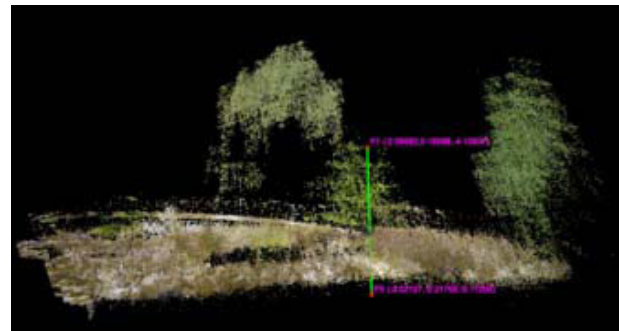
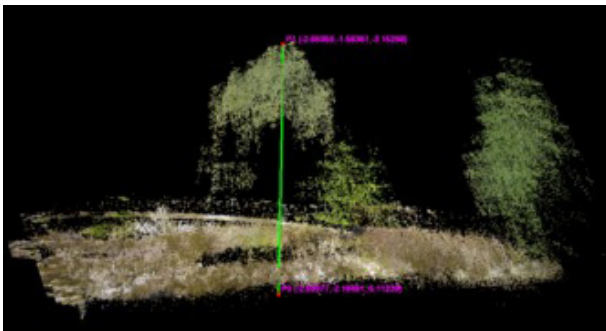
Automatic recovery of ground truth greatly shortened the duration of the study. Although image analysis has so far



Figure 15. An example of an acquired stereo couple.



Figures 16a, 16b. Two views of the points cloud extracted from the stereo couple (source: Petitpas).



Figures 16c, 16d. Two examples of measures that have been tested with the cloud point (source: Petitpas).

been done mostly manually in our test mission, it is possible to consider the use of automatic classification algorithms. In addition, we explained that this type of mission, unlike conventional missions, is less subject to weather constraints or even geographical constraints (such as hard-to-reach areas, such as volcanic areas), because the system is very easy to deploy and quick to use. Accordingly, missions can be programmed almost on demand. As a result, they are more adapted to the phenological cycles of plants.

The classification accuracy, the speed of acquisition and analysis, and the ability to easily perform repeated acquisitions are three factors that allow us to consider the use of these methods and tools in studies of pest plants. Indeed, to counter these invasions, we need to monitor the evolution of species in an area and to dynamically map them. This must be done in order to detect abnormal proliferation of one of these species as soon as possible, even though their individuals may still be at an early stage in their evolution. The type of map produced with the Extended Ground Truth Methodology can therefore be one of the critical pieces of data used to prevent the emergence of such risk situations.

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