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DETECTING DITCHED SITES ON LIDAR-GENERATED DIGITAL ELEVATION MODELS

From technical specifications to interpretation keys

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Remote sensing devices now provide operators and scientists with a wealth of information which, due to poor accessibility to forests and exploration costs, could not be collected from ground data alone (Maltamo *et al.* 2014). As such, light detection and ranging (LiDAR) technology has been used in archaeological surveys for the past several years (Bilodeau and Deroin 2008; Chase *et al.* 2012), allowing archaeologists to overcome the constraints of dense forests and to better position sites within landscapes.

Briefly, LiDAR, or airborne laser, is a remote sensing technique designed to acquire three-dimensional, high-spatial-resolution data. It functions by emitting high-frequency laser pulses from an emitter embedded in an aircraft (airplane, helicopter, microlight, unmanned aerial vehicle [UAV], etc.). The laser pulse emitted from the aircraft is reflected by the various targets it encounters: leaves, branches, trunks, ground. A sensor embedded in the aircraft (the 'scanner') records the return signal and return time of the wave in order to deduce the distance to the target. The resulting point cloud corresponds to the XYZ coordinates of all targets, calculated in accordance with the scanner's position and the direction of its beam (Khan *et al.* 2017; White 2013).

A digital elevation model (DEM) of the terrain can be generated after filtering the points corresponding to the ground. Prior to this ground point filtering, a preprocessing of the raw data is required. It typically includes fine co-registration of flight lines and noise filtering. Once the ground points are extracted, an interpolation step is required to produce the DEM (Chen *et al.* 2017).

The various methods for processing and visualising this data make it possible to identify (micro-)topographical irregularities, some of which may correspond to archaeological structures. In Amazonia, LiDAR technology is routinely used to create DEMs as part of development projects, as well as for mineral, hydrological and forestry exploration. In recent years, a number of pre-Columbian artefacts have been uncovered (see Chapter 1), such as geoglyphs (Khan *et al.* 2017), ponds or cavities (Stenborg *et al.* 2018) or even cities and conurbations (Fisher *et al.* 2017; Canuto *et al.* 2018).

In French Guiana, ditched sites have been identified using this kind of data (Mestre *et al.* 2008), and geovisualisations of 'ring-ditched sites' have gradually appeared in the scientific sphere and received media attention. The French term '*montagne couronnée*' (i.e. crowned mountain) is used by some local communities to describe the presence of deep ditches encircling hilltops. It first appeared in archaeological literature in 1952 (Abonnenc 1952). Those ditches are always described as more or less backfilled canals, sometimes to the point of appearing as terraces, encircling a hillock that usually dominates the surrounding landscape. The diameter, depth and width of the ditches vary. They may be sealed off in two or three places as if to make passages. Two other less common types of ditched sites in the Guiana Shield are the 'promontory fort', where a straight ditch blocks the only easy access to the top of a steeply sloping hill, and the plateau site, where a more or less circular ditch is located on a flat plateau area, often near its edge. Many combinations between these different modalities are also observed.

Data acquisition: what technical specifications are required?

LiDAR data are now widely used by scientists and other operators to make environmental assessments, establish risk prevention plans (flooding, erosion), map forest stand structure, detect holes, delineate individual tree crowns, etc. These different uses require technical specifications which may vary (planimetric or altimetric accuracy, type of sensor, emitted pulse density, etc.). Therefore, before any acquisition campaign, consideration must be given to the minimum specifications for obtaining data which can be used to detect ditched sites.

The accuracy and precision of the DEM are primarily determined by the mean density of the ground points and the regularity of their spatial distribution. The density of ground points will depend on a number of acquisition parameters. First, the emitted pulse density sets an upper bound to the final ground point density. However, because in forested landscapes much of the laser wave is intercepted before reaching the ground, a number of other characteristics may affect the final density of ground returns. The power of the laser, the size of the laser beam footprint, the maximum number of returns per emitted pulse[1] and the height of flight jointly determine the penetration – i.e. the ability of the laser to detect the ground below the canopy. The emission angle also affects the penetration, as laser pulses sent at angles farther away from the vertical will have to travel a longer distance through the canopy before reaching the ground and will therefore be less likely to trigger a ground return.

The regularity of the spatial distribution of ground points is expected to increase with laser power or if flight height is reduced. Increasing pulse density will increase total ground point density proportionally, but may not significantly improve regularity.

Under typical settings over dense tropical forest, between 2% and 6% of the pulses will reach the ground with enough energy to produce a detectable return. By way of comparison, in the less dense forests of Guatemala, this value averaged 8.6%, within a range of 3.7% to 24% (Canuto *et al.* 2018).

From digital elevation model generation to its interpretation

Once the DEM is produced, a series of analyses can be conducted to characterise the local topography. Aspect, slope or sun exposure are readily computed using dedicated routines available in standard geographic information system (GIS) software. As ditches may be of limited width and depth, as well as partly eroded, it is recommended to use a high-resolution DEM. According to the sampling theorem, a linear object such as a ditch cannot be detected below the Nyquist limit, i.e. if the resolution is less than half the ditch width (e.g. 2 m/pixel for a 4-m-wide ditch) (Hengl 2006). It is worth noting, however, that the human eye will be able to identify the artefactual nature and reconstruct the geometric shape of a ditch, even if it is not visible over its entire length.

Mapping of archaeological remains in general, and ancient ditches in particular, is still largely a manual operation, given the complexity and multiplicity of factors to be considered (de Matos Machado *et al.* 2016). Here we describe a five-step simple and structured method of processing DEMs from aerial LiDAR for manual detection of ring-ditched sites in tropical forests. It has been developed and applied to more than 2500 km^2 of data acquired in French Guiana as part of operations for various purposes (forestry, land use planning, mining exploration, etc.).

1 Check the overall accuracy of the DEM. It will depend on the reliability and density of LiDAR points, the gridding resolution, the interpolation method and the complexity (or roughness) of terrain features. Density and regularity should be sufficient to generate a 2 m/pixel DEM. Below a 2-m resolution narrow ditches will not be detected effectively.
2 Apply a hill-shade algorithm using similar parameters (sun elevation and azimuth) for all DEMs if more than one is being processed. A known limitation of the analytical hill-shade method is that it may fail to reveal linear features parallel to the light beam. Other visualisation strategies have been put forward to overcome such a limitation. Alternative methods (not tested here) include maps of sky-view-factor or slope gradient (Zakšek *et al.* 2011; Bennett *et al.* 2012; Štular *et al.* 2012). Slope map is recommended as a complement to hill shading (see step 4).
3 Apply a grid of 1-km^2 cells over the areas of interest (Figure 8.1). Scrutinise each cell in search of possible ditch shapes. The use of a grid allows for greater consistency in this visual examination by ensuring that all cells have been examined with equal attention. The elementary cell size was determined experimentally.

4 Areas with ditch-like structures are then further processed. New shade maps are produced by varying sun elevation and azimuth in order to better reveal the local microtopography. A slope map is also produced from the fine resolution DEM. Application of a vertical exaggeration factor may also prove helpful (Figure 8.2). Once a final diagnostic is made according to local topographic features, the site is marked and labelled.

5 The last step consists of describing the site and qualifying/categorising the artefact. This is done based on interpretation keys provided by archaeologists. Parameters considered are:

- shape, size and number of ditches (if more than one);
- relative and absolute height of the hilltop (dominance of the site);
- topographic position within the landscape (e.g. general exposure, proximity to rivers, lakes or marshland);
- associated works (access path, ditch crossing, summit levelling).

Limits of current methods and techniques

While this method has identified a number of previously unknown sites, its implementation conditions and limitations still need to be better defined, particularly before systematic application to Amazonian archaeological sites can be recommended.

First, most of the LiDAR data available in French Guiana and analysed here are located in a dense forest context. The restricted laser penetration and the generally low density of ground points obtained limit the resolution of DEMs and therefore the ability to detect archaeological structures. In our experience, acquisition densities around 6–10 points/m^2 and DEMs with a resolution of 2 m/pixel allow one to correctly identify ditches a few metres wide. We observed that such DEM resolutions were often not achievable with single-return LiDARs, resulting in the non-detection of sites that had previously been identified in the field.

More in-depth analyses must be carried out to better characterise the impact of acquisition density, but also of other acquisition parameters (scanning angle, laser power, etc.) and point clouds pre-processing (classification, outlier filtering, etc.), on ground point density and the resulting DEM quality. Similarly, DEM production parameters (interpolation methods, spatial resolution of rasters, etc.) can have an impact on the effectiveness of potential automatic site detection. The identification of optimal methods and settings is thus necessary both to understand the quality of the analysed data and to possibly reprocess the point cloud and generate a more suitable DEM.

While it is obviously desirable to have the highest densities of ground points to allow the finest possible DEM resolution, the uneven spatial distribution of points remains an important element at these scales of observation: in the data used here, we have often observed areas of several tens, or even hundreds, of square metres without ground points and therefore without any microtopographical data.

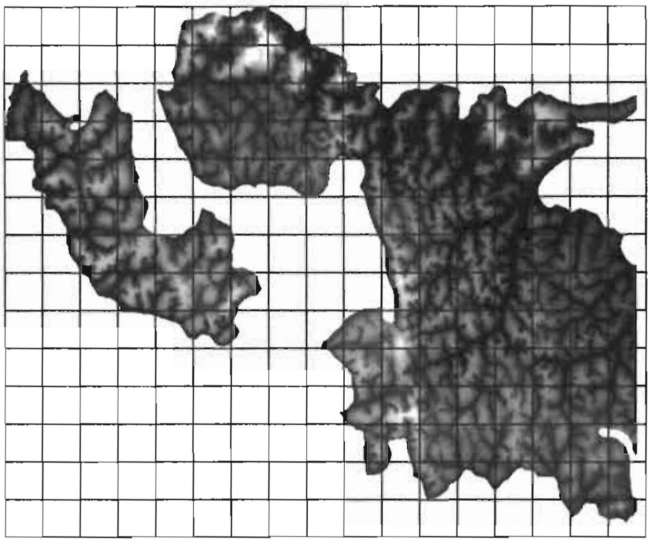

FIGURE 8.1 Two-metre resolution DEM of the Eastern part of Régina-Saint-Georges forest (Régina, Ouanary and Saint-Georges, French Guiana). The average pulse density is 13.2 points/m^2.

Source: © C. Bedeau/ONF.

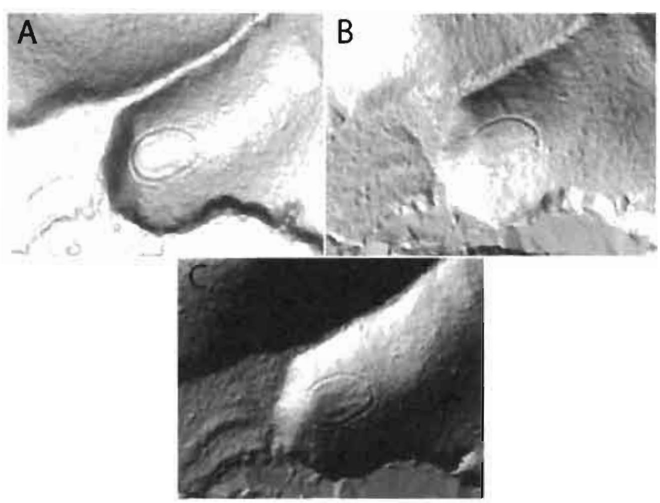

FIGURE 8.2 Three artificial views of a ring-ditched site detected on a 2-m resolution DEM of the North Mataroni area (Régina, French Guiana); scale 1:4000. **(A)** Slope map (vertical exaggeration = 2); the steepness increases from white to black. **(B)** North–west shading (azimuth = 45 degrees, elevation = 135 degrees, vertical exaggeration = 3). **(C)** North–east shading (azimuth = 315 degrees, elevation = 25 degrees, vertical exaggeration = 3).

Source: © C. Bedeau/ONF.

Additional information on the confidence of detections could thus be integrated into the method, for example, in the form of a confidence index or the quality of local microtopographic representation.

A good knowledge of the terrain is also often essential, either to be able to eliminate certain modern decoys such as traces of old forest tracks, mining excavations, etc., or to confirm the presence of a ditched site by a field check when there is still a doubt about the nature of the artefact observed on the DEM.

Finally, the method developed here is based solely on the processing and visualisation of DEM raster data, which is easier to handle and interpret in conventional GIS software than the raw LiDAR data, i.e. point clouds. Treatments carried out directly on the point clouds would certainly offer other perspectives for the identification of ground anomalies related to old structures of anthropogenic origin (White 2013). In particular, if ground point distribution is very irregular, direct examination of the triangulated irregular network (TIN) surface model may be useful to make the most of the densely sampled areas.

Conclusion

LiDAR has proven to be a powerful tool for generating detailed DEMs under dense canopy forests. Although LiDAR surveys remain expensive, the areas covered are becoming increasingly large, as the data acquired are useful for a variety of projects such as land-use planning, forest management or hydrological monitoring. At the same time, the power and pulse emission rates of sensors are continuously improving, allowing operators to fly higher, thereby reducing the cost per unit area. A significant constraint in the tropics is the frequent presence of low cloud cover, which often prevents one from taking full advantage of those technological improvements, as the LiDAR signal is affected by clouds.

Even if the data may be of a suboptimal standard, the study of the resulting DEMs is now the best, if not the only, way to detect in these low-visibility environments large but often inconspicuous structures such as partly eroded ditches. However, visual identification on a DEM and classification of ditches of different shapes and sizes is time-consuming. As more and more DEMs produced by LiDAR become available and larger and larger areas need to be processed, it may become necessary to automatise the screening using pattern recognition techniques (Trier and Pilø 2012; Lindberg *et al.* 2013; Verschoof-van der Vaart and Lambers 2019). Ultimately, human expertise and the time are required for a fine classification of artefacts and a field validation step are unavoidable for adjusting interpretation keys before they can be applied to the entire area of interest.

Although the areas already treated in French Guiana are still small compared to the size of the territory, the number of detected sites is surprising high, as is their diversity of shapes. Once this census is sufficiently extensive, prospects will then open up to consider a typology of these phenomena, based both on their geometric characteristics and the geographical context of their appearance.

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Note

1 With single-return LiDARs, only the return of the first or last object hit by the beam is recorded. Other types of devices can record the first and last hits, while the most recent systems ('multiple return') record the returns of several targets (usually up to five) that the beam may encounter on its path. Multiple-return LiDARs are likely to generate more ground points.

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