Establishment of mangroves on a new mud bank by a combination of UAS SfM photogrammetry and LiDAR monitoring

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Abstract

Understanding how mangroves respond to sea level rise is critical for coastal management and conservation. This study investigates the feasibility of two remote sensing techniques, Light Detection and Ranging (LiDAR) and Structure-from-Motion (SfM) photogrammetry, to monitor changes in mud elevation that are critical to mangrove establishment dynamics. SfM photogrammetry can provide low-cost 3D modeling from imagery, while LiDAR provides high-precision elevation and vegetation data. Our analysis shows that SfM photogrammetry provides reasonably accurate surface elevation data with a root mean square error (RMSE) of 0.14 meters and a significant correlation coefficient (r = 0.74) compared to LiDAR measurements. This highlights the complementarity between the two, as the effectiveness of SfM photogrammetry is in the early stages of colonization, and then the need to use LiDAR with dense vegetation as the mangroves mature. This shows that a simple method of photogrammetry can remain effective until the vegetation reaches a certain threshold, and this can be particularly useful in the perspective of using mud elevation as a first low-cost diagnosis for potential mangrove rehabilitation project to assess the colonization suitability of mudflats.

1. Introduction

The world's muddy coasts are particularly vulnerable to the effects of global change on sea level rise, loss of sediment supply, and increased coastal wave energy (Hulskamp *et al.* 2023). The coast of French Guiana (Figure 1) is controlled by complex interactions of waves and giant mudbanks. These latter migrate alongshore from the Orange Cap to the Orinoco River (Anthony *et al.* 2010). Mudbank migration induces alternating bank and interbank phases (Froidefond *et al.* 1988, Anthony *et al.* 2010). During the interbank phases, rates of mangrove retreat can reach 500 m per year while, during the bank phase, impressive patterns of mangrove seaward expansion can be observed over tens of square kilometers (Proisy *et al.* 2021). Mangroves can give us information about the coastal dynamics of French Guiana, allowing us to anticipate the vulnerability of the coast, since they disappear as quickly as the erosion phases are intense. What makes mangroves so interesting to study is their ability to regenerate in places where they have disappeared.

In order to assess the capacity for natural colonization and spatial expansion of mangroves, mud elevation (or ground elevation) is first needed to better understand the hydrodynamic and sedimentary processes at play (Fiot and Gratiot 2006, Proisy *et al.* 2009). Mud elevation level, linked with inundation duration, can influence the establishment success of a mudflat by mangrove seedlings (Balke *et al.* 2011, Oh *et al.* 2017). Then, it's necessary to understand the specific dynamics of the mangrove forest and its structure, with parameters such as the distance between the seafront and the mangrove stands, their density, but also individual characteristics such as tree height or the appearance of new seedlings (Fromard *et al.* 1998, Fromard *et al.* 2004, Yin and Wang 2019).

In the last decade, unmanned aerial system (UAS) has become a powerful tool for coastal environment monitoring (Brunier *et al.* 2016, Brunier *et al.* 2020), it enhances our ability to describe ecological processes using non-invasive methods such as soil degradation, provides access to remote areas, and facilitates time-consuming field methods that are difficult to implement due to the muddy environment in which mangroves grow (Flores-de-Santiago *et al.* 2023). The implementation of remote sensing analysis based on UAS, such as Structure-from-Motion (SfM) photogrammetry or Light Detection and Ranging (LiDAR) technologies, offers new perspectives that allow data to be collected more quickly, accurately and more frequently. Here, we try to show the complementarity between LiDAR and SfM photogrammetry in characterizing the mangrove colonization process. On the one hand, SfM photogrammetry is a low-cost technology that provides topographic information, such as Digital Surface Models (DSMs), by generating high-resolution 3D models from a series of 2D images taken from different angles (Mury *et al.* 2019). However, growing vegetation distorts ground elevation estimates and limits topographic information. On the other hand, UAS LiDAR provides improved ground

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access and can capture height information of vegetation with high accuracy and resolution (Guo *et al.* 2017). Using LiDAR and SfM photogrammetry UAS surveys can be essential tools for improving the understanding of the sedimentary and hydrological processes involved in the natural establishment of mangroves or rehabilitation project. Rehabilitation, is defined as the partial or complete replacement of the structural or functional features of an ecosystem that have been degraded or lost (Field 1999). Our work aims to to define when the use of each technology is more relevant by comparing the spatial distribution of ground elevation and vegetation.

2. Study area

The study area is located on the coast of French Guiana in South America, near the city of Cayenne (4°57’0 N, 52°19’12W). The climate is humid tropical. At least three alternating periods of mangrove development and destruction observed around Cayenne between 1950 and 2013. Since 2019, a new mudbank has been consolidating. Mangroves begin to colonize this newly formed mudflat between 2021 and 2022. To better understand how mudflat elevation affects mangrove establishment, since 2022 we have been monitoring 100 m² plots (Figure 1) where mangrove seedlings of two species, *Avicennia germinans* and *Laguncularia racemosa*, have developed.

3. Data acquisition

Three types of acquisitions were made for this project, a field acquisition to collect ground truth reference data, and SfM photogrammetry and LiDAR acquisitions, both using unmanned aerial system (UAS).

3.1 RTK-dGPS measurement of surface elevation

During the course of the study, two sessions of field measurements were carried out with a mobile RTK-dGPS unit at different locations on the mudbank to compare with the data recorded by the UAS surveys (Figure 1). Each measurement was taken at the base of a mangrove tree or seedling. The first session in mid-September 2023 consisted of 73 points at different locations on the mudbank. The second session of 20 dGPS measurements in mid-June 2024 focused on a smaller area of soft sediment where new young seedlings were starting to grow.

3.2 Repeated UAS photogrammetry and LiDAR surveys

A DJI Matrice 300 unmanned aerial system (UAS) equipped with a GNSS RTK receiver, an RGB camera for photogrammetric surveys, and a DJI Zenmuse L1 laser scanner payload for LiDAR surveys was used to observe the mudflat geomorphology and its spatial variability in detail.

SfM photogrammetry and LiDAR surveys were conducted simultaneously in pairs from October 2023 to June 2024 for a total of four flights (Oct. 20 for 2023 & Jan. 23, Mar. 11, Jun. 17 for 2024). Each flight was performed at low tide in clear meteorological conditions. To cover the 15 ha of the total area of mudflat shown above, each flight lasted 45 minutes and required the UAS to return to its base twice for battery changes During each flight, the RGB camera took a total of about 1000 photos of 5470 x 3650 pixels each, covering 0.4 ha at an altitude of 50 m.

In order to obtain a survey with centimeter accuracy, an RTK-dGPS positioning system consisting of a fixed ground station was set up before each flight for both types of surveys. The positions of each photo or point taken during the flight with the UAS's own RTK system were post-processed using the kinematic (PPK) method with the data recorded during the flight by the ground station. For each acquisition, ground control points (GCPs) were

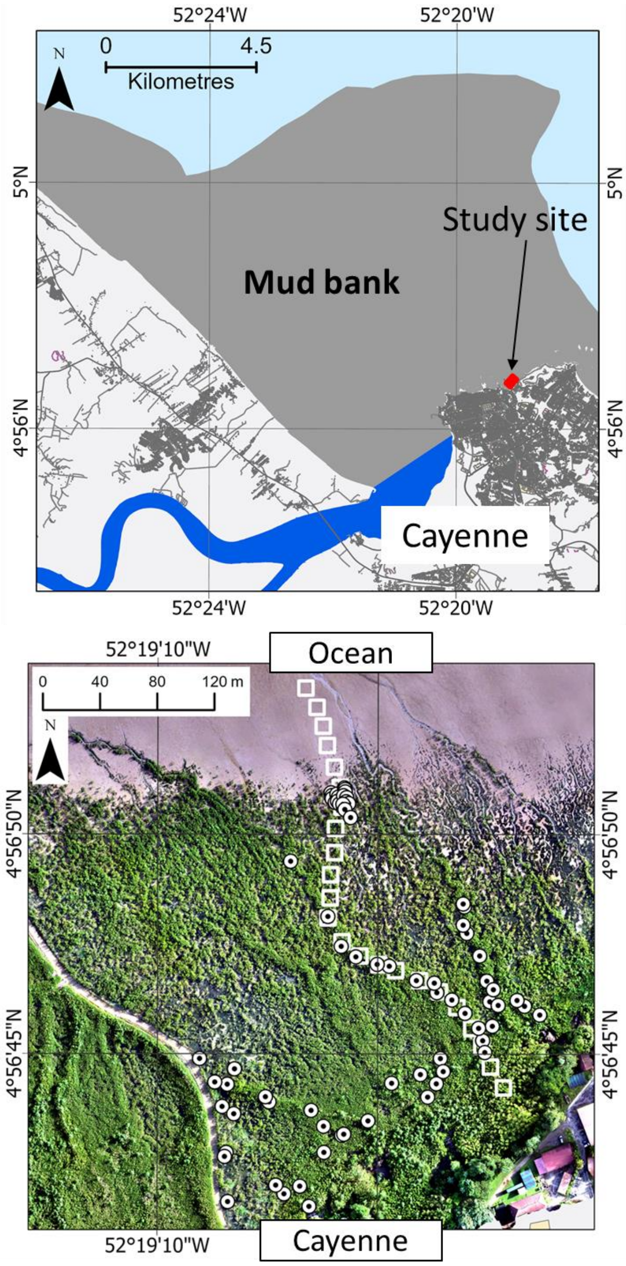

Figure 1. Top. The study area (small polygon in red), located on the seafront of the city of Cayenne. The grey area represents the extent and location of the mudbank in 2022, where mangroves are now developing. Bottom. A zoom of the colonized mud bank of the study area. The white squares represent the cross-shore transect made up of 10m x 10m areas. The white dots indicate the location of surface elevation measurements. The background image was taken in June 2024 and covers an area of 0.4 km x 0.4 km.

distributed in the field. The X, Y and Z positions of the GCPs were recorded with a mobile RTK-dGPS unit to allow accurate realignment of the SfM photogrammetric and LiDAR survey outputs. For the SfM photogrammetry, the post-processing was implemented with REDtoolbox® software. The GCPs were in the form of four black and white grid panels. For LiDAR, the post-processing was carried out using DJI Terra® software. In this case, two GCPs were distributed in the field as two red circle panels.

3.3 Numerical models from SfM photogrammetry and LiDAR

The SfM photogrammetry method was used to generate a three-dimensional Digital Surface Model (DSM) from each photogrammetric survey, providing an altimetric description of the ground and it's natural and built features. A workflow using Agisoft Metashape® software was used for this purpose (Over *et al.* 2021). The workflow relies on the alignment of the photographs taken by the RGB camera, based on the detection of tie points for each overlapping pair of photographs, and generates a dense model of X, Y, Z points together with a refinement of the position and orientation of each photograph in the 3D georeferenced system, which is the Universal Transverse Mercator 22 North zone projection associated with the Geodetic Network of French Guiana 1995 datum (UTM 22N RGFG 1995 in French; EPSG: 2972). An orthomosaic image with a spatial resolution of 0.02 m was generated from the set of UAS camera images using the same workflow. Surface interpolation was performed over the dense point cloud to generate DSMs. DSMs are obtained with an accuracy of 2.5 cm in the X, Y and better than 5 cm in the Z dimension.

The UAS LiDAR data were used to generate spatial products for each survey, in addition to a DSM, a Digital Terrain Model (DTM), which is an altimetric description of the ground, and a Canopy Height Model (CHM), which gives the height of vegetation above the DTM (Li *et al.* 2005). First, the laser scanner data was opened in the proprietary DJI Terra software to pre-process the point cloud for export in LAS format and in the georeferenced system. Then the alignment in Z was done with the strip alignment implemented in BayesStripAlign 2.18 software (Bayesmap Solutions 2020) enhanced by an alignment with the two GCPs. The classification part of the cloud point was done on the C++ library Point Data Abstraction Library (Butler *et al.* 2021) via the Simple Morphological Filter (SMRF)(Pingel *et al.* 2013) to classify the points as ground or not ground. Then, DTMs with a spatial resolution of 30 cm are generated from a linear interpolation of the Triangular Irregular Network (TIN) derived from the ground points. In parallel, CHMs were processed using the "pit-free" algorithm (Khosravipour *et al.* 2014). Subsequently, an SfM DSM classification of soil and vegetation was performed using the LiDAR CHMs as a reference. The reliability of the DSMs and DTMs generated from each survey was successfully confirmed using additional natural and fixed bedrock targets.

4. Result

The comparison of surface elevation measurements obtained from SfM photogrammetry and LiDAR with RTK-dGPS surface elevation shows that SfM elevation points are more widely scattered along the y-axis compared to LiDAR elevation points. The 1:1 line, which represents perfect agreement with RTK-dGPS measurements, shows that the LiDAR elevation data are clustered closer to it, while the SfM elevation data are more spread out, further highlighting the higher variability of SfM measurements (Figure 2. Top). SfM photogrammetry has a higher root mean square error (RMSE) of 1.96 m and a weak correlation coefficient (r = 0.25) with ground truth data, indicating lower accuracy and reliability. In contrast, LiDAR data has a significantly lower RMSE of 0.19 m and a stronger correlation coefficient (r = 0.60), indicating superior accuracy and reliability in surface elevation representation.

Furthermore, the direct comparison of SfM photogrammetry and LiDAR derived elevation values (Figure 2. Bottom) shows an RMSE of 0.14 meters and a robust correlation coefficient (r = 0.74), indicating a strong positive correlation between the two datasets. Notably, 98.5% of the data points are closely aligned along the 1:1 line, demonstrating a high level of agreement between SfM and LiDAR measurements within this range. However, discrepancies appear on the y-axis, where the SfM measurements tend to overestimate the LiDAR measurements because SfM cannot correctly evaluate ground elevation in the presence of vegetation.

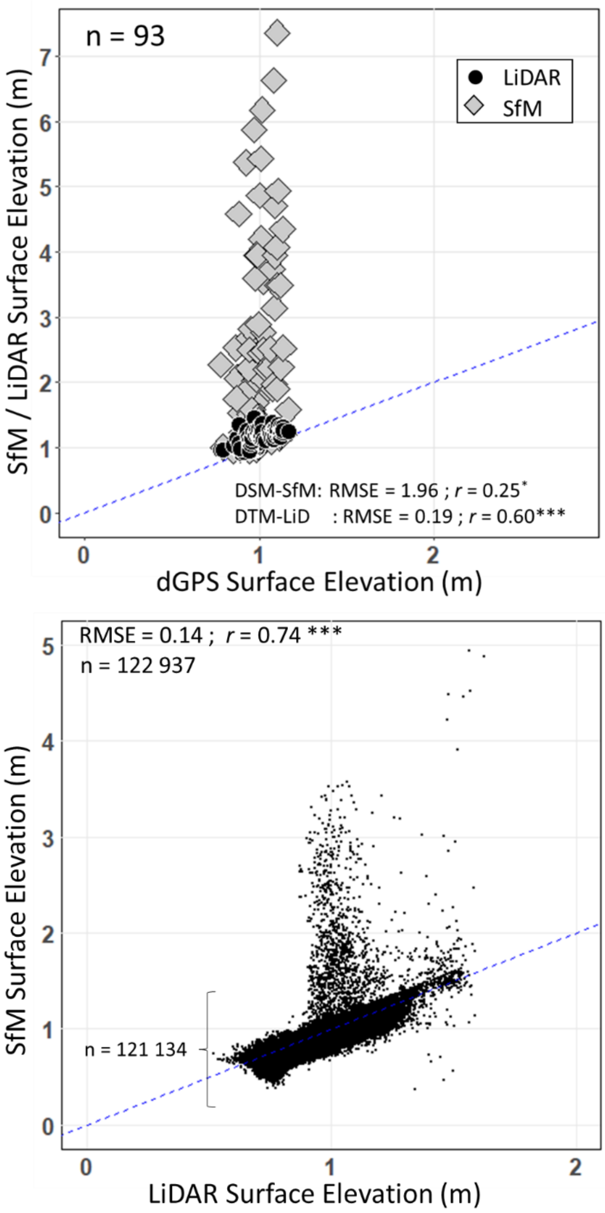

Figure 2. Top. Comparison of Elevation data from SfM photogrammetry and LiDAR with field ground truth. Bottom. SfM photogrammetry ground surface elevation values versus LiDAR surface elevation values. The root Mean Square Error (RMSE) and correlation coefficients (r) using the pearson method were calculated. The dashed blue line indicates the 1:1 reference line.

For each survey, the LiDAR DTM shows a consistent surface elevation between each station along the land-ocean transect (mean elevation: 1.07 m ± 18 cm), and a vertical uncertainty of about 7 cm per survey, indicating stable ground elevation measurements (Figure 3). In contrast, the DSMs derived from SfM photogrammetry shows considerable elevation variability between each station along the transect (mean elevation: 2.4 m ± 2.1 m), and a higher vertical uncertainty of about 88 cm per survey, especially when mangroves are significantly developed, i.e. CHM>2 m. This variability suggests that vegetation has a significant impact on surface elevation measurements for photogrammetry, as the uncertainty decreases significantly to ± 4 cm when vegetation cover is less than 10%. In addition, the mean elevation difference between LiDAR and SfM photogrammetry remains minimal in areas without vegetation (mean difference: 4 cm ± 4 cm), but increases with the extent of vegetation cover, reaching the highest values (mean difference: 3.3 m ± 88 cm) when the area is completely covered by vegetation, which correlates with the height of the vegetation (r=0.91***). The Canopy Height Model (CHM) observation is consistent with the elevation differences between DSM-SfM and LiDAR DTM and effectively delineates vegetation height, with notable changes observed between different dates, indicating natural growth patterns.

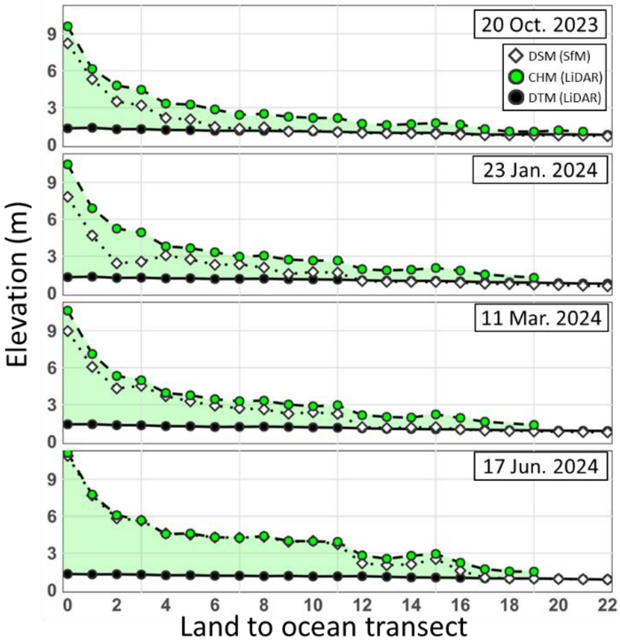

Figure 3. Surface elevation from SfM photogrammetric DSM and LiDAR DTM. The dotted line represents the CHM showing the average vegetation height of each station for each date above the soil elevation measured in the Lidar DTM. The green band represents the presence of vegetation in the transect.

5. Discussion

The results of this study show that LiDAR and SfM photogrammetry derived data provide comparable elevations for monitoring exposed mudflats. This alignment suggests that both techniques can be effectively combined to ensure consistent and accurate monitoring of such environments. Structure from Motion (SfM) photogrammetry does not provide accurate ground elevation information when applied to vegetated areas : the accuracy decreases as the mangrove seedlings develop. However, the use of Digital Surface Models (DSMs) derived from SfM can provide vegetation elevation data, although it falls short of determining precise vegetation height with the lack of precise ground elevation to create a CHM. Consequently, SfM photogrammetry should be prioritized for ground elevation monitoring in scenarios where vegetation is either sparse or absent to ensure accuracy and reliability.

Due to the importance of elevation in structuring of the mudflat (Fiot and Gratiot 2006), its monitoring plays a key role in understanding the dynamics of natural mangrove establishment and, in particular, in characterizing inundation-free periods for seed establishment (Fiot and Gratiot 2006, Proisy *et al.* 2009, Balke *et al.* 2011, Gensac *et al.* 2011). Colonization events require inundation-free periods to allow sufficient time for root development to withstand hydrodynamic forces (Balke *et al.* 2014), and a drop in elevation of just 30 cm can be enough to nearly triple the frequency of flooding (Watson 1928). The use of SfM photogrammetry, which is becoming increasingly accessible and low-cost, can quickly assess the surface elevation situation in order to know if there are suitable conditions for mangrove development. On the one hand, when assessing the capacity of mudflats for mangrove colonization, it is important to recognize that where the process is already underway, minimal intervention is required and can serve as a reference state. These sites naturally have the appropriate conditions for mangrove establishment and growth, allowing them to colonize independently. On the other hand, the diagnosis of bare mudflats or areas destined for rehabilitation requires a more detailed assessment, where it is critical to evaluate the surface elevation prior to initiating any planting efforts (Oh *et al.* 2017). This can help in the rehabilitation and development of fragile coastlines, such as in Guyana, where extensive artificialization has occurred and mangroves are not as abundant as they once were (Anthony and Gratiot 2012).

Overall, the results show that SfM photogrammetry provides reasonably accurate surface elevation data, although LiDAR remains the more accurate method mostly when the vegetation became too dense. More low-cost, SfM photogrammetry enable to monitor the mudflat elevation only in the first phase of mangrove colonization. This limitation underscores the growing importance of Light Detection and Ranging (LiDAR) technology in ecological studies. LiDAR, with its advanced radar-based capabilities such as high emission density and small beam diameter, provides superior ground access by effectively penetrating vegetation layers. This results in a more accurate point cloud representation of the ground surface, which is critical for producing high-quality Digital Terrain Models (DTMs). Conversely, photogrammetry faces significant challenges in similar environments due to its inability to penetrate dense vegetation canopies to reach the ground surface. As vegetation density increases, the accuracy of photogrammetric methods in mapping the ground surface decreases (Rogers *et al.* 2020, Štroner *et al.* 2023). This advantage of LiDAR is particularly valuable in the later stages of mangrove colonization, when understanding both soil properties and the structure of the overlying vegetation is critical.

Conclusion

The study underlines the effective integration of LiDAR and Structure from Motion photogrammetry in mudflat monitoring and highlights their complementary strengths. While SfM photogrammetry is useful for assessing ground elevation in sparsely vegetated areas, it's accuracy decreases as vegetation density increases, requiring the superior capabilities of LiDAR for more accurate data. LiDAR's advanced radar-based technology enables accurate mapping of the vegetation and the ground surface by penetrating it. Assessing the evolution of mud elevation and monitoring the expansion of mangroves provides us with essential information for the natural recovery of the ecosystem and the conservation of coastal biodiversity, thus helping to improve the methods of rehabilitation of these ecosystems.

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