Structure-from-Motion photogrammetry for high-resolution coastal and fluvial geomorphic surveys

Application de la technique de photogrammétrie « Structure-from-Motion » pour des levés haute résolution en géomorphologie côtière et fluviale

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**ABSTRACT**

Photogrammetry is an old remote sensing technique that has undergone significant new developments related to the emergence of new computer vision algorithms, notably the workflow technique called Structure-from-Motion (SFM photogrammetry). These innovations facilitate the utilization of this technique by non-specialists. SFM photogrammetry now enables the production of high-resolution morphometric 3D models and derived products such as digital surface models (DSMs) and orthophotographs. We conducted three SFM-photogrammetric experiments, in French Guiana on an embayed beach in Cayenne and on a small mudflat sector of a coastal mud bank near the Sinnamary estuary, and finally in the French southern Alps on a section of the braided Buëch River near Sisteron. We developed a simple field protocol based on subvertical aerial photography from a microlight aircraft at low altitude (1000 feet). We generated DSMs and the other products with user-friendly Agisoft Photoscan Professional software. These SFM implementations were aimed at highlighting the subtle morphological variations characterising these features and some of the processes involved in morphological change. The DSMs were produced at a resolution of 5 to 10 cm per pixel and had a mean vertical accuracy less than 10 cm compared to the Real-Time Kinematic Differential Global Positioning System (RTK-DGPS) control points, with a maximum of 20 cm in marginal sectors near high vegetation such as trees and shrubs and on wet surfaces close to water-filled channels or in the lower intertidal zone. Low-cost, user-friendly SFM photogrammetry offers interesting new perspectives in the fields of coastal and fluvial geomorphology requiring high-resolution topographic data. The technique combines the advantages of the reproducibility of GPS topographic surveys and the high density and accuracy of airborne LIDAR, but at very advantageous cost compared to the latter.

**Keywords:** SFM photogrammetry, high resolution DSM, morphometry, beach, mudflat, braided river.

**RÉSUMÉ**

La photogrammétrie est une technique ancienne de télédétectio qui connaît des développements significatifs liés à l’émergence des algorithmes de vision assistée par ordinateur, comme la technique nommée « Structure-from-Motion » (photogrammétrie SFM). Ces innovations facilitent l’utilisation de cette technique par des non-spécialistes. La photogrammétrie SFM permet aujourd’hui la production de modèles morphométriques haute résolution et de leurs produits dérivés comme des modèles numériques de surface (MNS) et des orthophotographies. Nous avons effectué trois expériences de photogrammétrie SFM : en Guyane française sur une plage de baie à Cayenne et sur un étroit secteur d’une vasière intertidale associée à un banc de vase près de la ville de Sinnamary, puis dans les Alpes du Sud sur une section de la rivière en tresse du Buëch près de Sisteron. Nous avons développé un protocole de terrain accessible basé sur des photographies aériennes sub-verticales à partir d’un aéronef ultra léger motorisé (ULM) volant à basse altitude (1000 pieds). Nous avons généré les MNS et les autres produits dérivés à l’aide du logiciel Agisoft Photoscan Professional. Ces applications de la technique de photogrammétrie SFM ont pour objectif de souligner les variations morphologiques fines caractérisant les objets étudiés ainsi que les processus morphogènes. Les MNS ont été produits avec une résolution de 5 à 10 cm par pixel et ont une précision verticale moyenne inférieure à 10 cm au regard des points de contrôle levés à l’aide du GPS différentiel cinématique (i.e. RTK-DGPS), avec un maximum de 20 cm dans certains secteurs marginaux près de la végétation haute avec des arbustes et des arbres et sur les surfaces humides près de chenaux actifs ou dans la zone intertidale. Peu coûteuse et facile d’utilisation, la technique de photogrammétrie SFM offre des perspectives novatrices dans les champs de la géomorphologie côtière et fluviale requérant des données topographiques haute résolution. Cette technique combine les avantages de la reproducibilité des levés topographiques GPS et la haute densité et la précision des données issues du LIDAR aéroporté, mais à coût très avantageux comparé à ce dernier.

**Mots clés :** photogrammétrie SFM, MNS haute résolution, morphométrie, plage, vase intertidale, rivière en tresse.
1. Introduction

Accurate high-resolution topographic monitoring is increasingly employed to enhance our understanding of geomorphic processes in dynamic environments such as beaches and rivers. Several techniques are used to reconstruct the morphometry of a study site. These are total stations, differential global positioning systems (DGPS), airborne Light Detection And Ranging (aLiDAR), terrestrial laser scanning (TLS), and Structure-from-Motion (SfM) photogrammetry using different platforms such as unmanned aerial vehicles (UAVs), microlight aircraft, kites and poles. However, each of these techniques has operational and quality constraints in terms of cost and reproducibility, coverage, point density and accuracy, which render some of them inappropriate for very accurate monitoring of short-term changes affecting geomorphic features (Passalacqua et al., 2015).

Features such as beaches composed of quartz sand, mudflats, and river channel beds are commonly characterised by subtle and poorly contrasted morphologies, and by features ranging in elevation from a few centimetres to 1 metre, such as beach cusps, bedload accumulations, erosion scarp or micro-drainage channels. They are also characterised essentially by homogeneous textures and water-saturated surfaces. They also represent dynamic sites and unstable environments, such as beaches and mudflats, with potentially rapid morphological changes caused by waves or tidal currents, or exposed to rapid changes generated by water level variations or flash floods, such as braided rivers. These constraints imply that very high-resolution and accurate geomorphic mapping of these landscapes cannot be optimally operated using classical surveys with RTK-DGPS or a total station. Although these techniques allow for repeated surveys, the density of field measurements is generally sparse and does not allow for capture of subtle morphologies over large areas. Moreover, these methods require extensive surveys in time. Consequently, the only recent techniques suitable for such environments and capable generating very high-resolution and high-density data are aLiDAR, TLS, and aerial SfM-photogrammetry. However, the selected method must also withstand the constraint of frequent repetition in order to capture the medium-term dynamics, and this excludes expensive methods such as aLiDAR. Finally, TLS suffers from deployment range limit over spatial scales greater than hundreds of metres (James et al., 2013).

Photogrammetry is an old remote sensing technique notably used in the past to produce topographic information and orthophotographs. This once elaborate and laborious technique that necessitated specific expertise and analytical equipment has, over the last decade, undergone significant new developments notably to the workflow technique called Structure-from-Motion (SfM). SfM photogrammetry uses standard cameras for the photographic surveys and replaces the need for precise information on attitude and position on the pictures by least squares bundle adjustment algorithms which align pictures and produce a surface point cloud in a relative Cartesian three-dimensional referential (James and Robson, 2012, 2014). This first alignment is georeferenced and optimised by the use of ground markers measured by RTK-DGPS. Finally, the point cloud is rendered dense by multi-view stereopsis algorithm (Furukawa and Ponce, 2010). These innovations are integrated in semi-automated workflow schemes in several commercial and open-source software packages that facilitate the utilization of this technique by non-specialists. SfM photogrammetry now enables the production of high-resolution 3D models and derived products such as digital surface models (DSMs) and orthophotographs. Moreover, in the case of aerial photographic surveys, the vessels on which were embarked cameras, initially aircraft, have evolved towards more lightweight and flexible carriers such as UAVs, microlight aircraft, helicopters or kites (Delacourt et al., 2009; Bryson et al., 2013; Javernick et al., 2014; Tonkin et al., 2014; Gonçalves and Henriques, 2015; Smith and Vericat, 2015; Brunier et al., 2016). These new developments are leading to the emergence of SfM-photogrammetry as a low-cost, reproducible and high-resolution alternative to lasergrammetry techniques or traditional topographic survey techniques used by geomorphologists (Westoby et al., 2012; Fonstad et al., 2013; Hugenholtz et al., 2013; Javernick et al., 2014; Tonkin et al., 2014; Gonçalves and Henriques, 2015; Smith and Vericat, 2015).

SfM photogrammetry has been applied at various resolutions and levels of accuracy in the mapping of outcrops and landforms (Marzolf and Poesen, 2009; Westoby et al., 2012; Ouédraogo et al., 2014a,b; Smith and Vericat, 2015), and of a braided river (Javernick et al., 2014). The coastal implementations based on SfM-photogrammetry are also expanding, as the technique is now used for the morphodynamic study and reconstruction of complex coastal landforms such as beaches (Delacourt et al., 2009; James et al., 2013; Casella et al., 2014; Jaud et al., 2014; Gonçalves and Henriques, 2015) and cliffs (Gienko and Terry, 2014; Ružić et al., 2014). In this paper, we present SfM-based photogrammetry applied to three sites: a rapidly rotating embayed beach under the influence of mud banks drifting alongshore from the mouth of the Amazon near Cayenne, a mudflat associated with one such mud bank near the Sinnamary estuary, both in French Guiana, and a braided river in the French southern Alps where morphodynamics is studied to quantify solid sediment fluxes and the possible impact of engineering on channel bed morphology. Each of the monitored sites had a length of the order of a few kilometres, a width of a few hundred metres, and a size of 1 to 10 km². We show here that aerial SfM-photogrammetry can be implemented on poorly contrasted morphologies in very dynamic environments in order to produce very high-resolution Digital Surface Models (DSMs) of 5 to 10 cm per pixel with an accuracy with +/- 10 cm, and this paper is original in so far as it demonstrates that this method can be used to quantify geomorphic changes and sediment dynamics. Our field protocol is very easy to organize and the powerful SfM workflow is operated using user-friendly software. We use the same generic protocol for the three sites. The field sites, SfM protocol and results are presented below, followed by a discussion and concluding remarks.

2. Study sites

Montjoly beach is a 5 km-long sandy beach bound between two bedrock headlands in Cayenne, French Guiana (fig. 1A-B). The beach is periodically affected by massive mud banks that migrate alongshore from the mouths of the Amazon River in Brazil to those of the Orinoco in Venezuela (Anthony et al., 2010, 2014). Montjoly and the rare sandy beaches on this muddy South American coast are important economically and ecologically. They are recreational zones, but also nesting sites for protected marine turtles (Lepidochelys olivacea, Chelonia mydas, Eretmochelys imbricata, Dermochelys coriacea). The presence of mud significantly alters the behavioural patterns of Montjoly and the other sandy beaches, notably generating a form of beach rotation (Anthony et al. 2002; Anthony and Dolique, 2004) unique at the world scale. Such rotation does not result from variations in deep water wave approach directions, but from short to medium-term (order of a few years) changes in nearshore bathymetry induced by the migrating mud banks. These bathymetric changes affect wave refraction and dissipation patterns, inducing strong longshore gradients in waves that generate, in turn, lateral movements of sand in these headland-bound beaches, resulting in alternations of erosion and accretion areas over time that define this rotation. Anthony and Dolique (2004) defined these beach morphological changes in terms of a simple, four-stage conceptual model comprising bank, inter-bank
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Fig. 1 – General settings of our study sites in French Guiana and the French Southern Alps.

(A) French Guiana coastal context under the influence of massive mud supply from the Amazon. For more details, see Anthony et al. (2010). (B) Rotation of Montjoly beach near Cayenne, from the October 2014 orthophoto, corresponding to a transitional phase when mud banks migrate alongshore. See the rotational model of beaches under mudbank influence in Anthony and Dolique (2006). (C1) Large mudbank near the Sinnamary estuary. A consolidation gradient of mud deposits is clearly visible, associated with specific coastal landforms such as a mangrove island and a mud "tombolo". (C2) Focus on the mudflat site, comprising consolidated mud deposits with microforms such as decimetre-scale pits and drain channels. (D1) Regional setting of the Buëch River catchment in the southern French Alps. (D2) Focus on the photogrammetric experimentation site upstream of the engineering gravel trap structure. The channel shows a braided pattern and becomes more channelized with a decreasing number of interfluves in narrow sections of the valley.

Fig. 1 – Présentation des sites d'étude sur le département de Guyane et dans les Alpes du Sud.

(A) Contexte côtier du département de Guyane sous l'influence du système de dispersion régional des sédiments du fleuve Amazone. Pour plus de détails, voir Anthony et al. (2010). (B) Rotation de la plage de Montjoly près de Cayenne à partir de l'orthophotographie produite en octobre 2014, correspondant à la phase de transition lorsque un banc de vase migre le long de la côte. Voir le modèle de rotation des plages sous l'influence d'un banc de vase dans Anthony et Dolique (2006). (C1) Vaste banc de vase près de l'estuaire du fleuve Sinnamary. Un gradient de consolidation des dépôts vaseux est clairement visible, associé à des morphologies côtières spécifiques comme une île de mangrove connectée à la côte par un "tombolo" de dépôts vaseux récents. (C2) Zoom sur la vasière intertidale étudiée, constituée des dépôts vases consolidés formant des micromorphologies de chenaux de drainage et de vasques d'échelle décimétrique. (D1) Emprise régionale du bassin versant du Buëch dans les Alpes du Sud. (D2) Zoom sur le site d'expérimentation de la photogrammétrie en amont de l'aménagement d'un piège à gravier. La géométrie du chenal montre un système en tresse en cours de chenalisation avec une décroissance du nombre d'interfluves vers l'aval dans les sections étroites de la vallée.
and transitional phases, that are characterised by dramatic beachface retreat or advance of up to 100 m in two to three years.

Our second implementation of SfM photogrammetry concerned an intertidal mudflat affected by constant muddy accretion and mangrove colonization. This site is part of a larger multi-disciplinary experimental site on mangroves located in the western part of the Sinnamary river estuary (fig. 1A, fig. 1C1-C2). The Sinnamary mud bank is several km-long, and wave reworking of its surface creates mudflats and a succession of longshore mud bars, both colonized by mangrove. Mud bars and mangroves dissipate wave energy, enabling progressive muddy coastal accretion. The study site shows three levels of mud deposits: fresh water-saturated mud during low tide and exhibiting a very smooth surface morphology, consolidated mud drained by microchannels at low tide, and characterised by numerous water-filled pits on the surface that are probably collapse features due to bioturbation by macro-organisms and desiccation faults, and, finally, bare consolidated mud that may be colonized by mangroves in places. In this study, we focused on consolidated mud without mangrove.

The downstream portion of the Buëch River is good example of an engineered braided river (fig. 1D1-D2). The system comprises a 150 m-wide channel bed flanked by erodible banks of marl and characterised by a highly mobile braided network. The bedload is composed of calcareous gravel and pebbles with sand. The Buëch is a subalpine system influenced by both Mediterranean and mountain climates that create variable hydrological and sediment transport conditions (Brisset et al., 2014). The watershed drains an area of 1477 m² covering sections of the southern French Alps mountain ranges of the Dévoluy, the Vercors, the Gap basin and the Baronnies (fig. 1C). The influence of Mediterranean climatic conditions is reflected in variably intense autumn rainfall and summer drought, while the mountain influence induces cold winter conditions. As a result, the Buëch is characterised by a bimodal torrential flow driven by snow melting and autumn rain floods. The channel network is composed of three main tributaries: the Grand Buëch and the Petit Buëch upstream of Saint Saviour dam, and the Méouge river downstream. The Buëch joins the Durance River at Sisteron.

The Buëch is highly engineered: numerous dams were constructed on the river, and its bed subject to extractions of sand and gravel since 1950. Despite these extractions, the bedload transport capacity remained high and induced a rise in bed elevation near the city of Sisteron that increased significantly the flood risk in several districts of the city. Consequently, an alluvium mitigation plan was implemented over the last decade with the construction of a gravel bedload trap structure in 2010. This structure stops the bedload transport upstream of the Saint Lazare dam and enables concentrated localized dredging of the bed, rather than the more expensive dredging that was hitherto necessary throughout the reach upstream of the dam. Since 2011, the trap has stopped sediment aggradation inside and upstream the dam reservoir thus reaching the risk mitigation goal.

3. Method

The SfM photogrammetry protocol described in this article is very accessible to non-photogrammetrists. In this section, we summarise briefly our method (fig. 2), but the reader is referred to the works of Javernick et al. (2014), Ouédraogo et al. (2014b) and Brunier et al. (2016) for more detailed protocol presentations. Basically, photogrammetry is a technique for reconstructing objects in 3D from 2D stereoscopic images. Some limitations are intrinsic to the technique, such as water surfaces that cannot be measured because of specular reflection and the lack of coherence between consecutive images. Moreover, on homogeneous surfaces such as sand, the lack of texture makes it impossible to identify homologous points and thus to correlate images.

First, we operated photograph collection in each site (fig. 2). This phase combines the aerial photographic survey and ground operations. Three flights were operated over Montjoly beach in October 2013, March 2014 and October 2014, one flight near the gravel trap on the Buëch River in March 2014, and one flight in October 2014 above the Sinnamary mudflat. The aerial photographic surveys were carried out using a microlight aircraft, an autogyro in the case of the Buëch River and a fixed-wing aircraft for Montjoly beach and the Sinnamary mudflat. Concerning the coastal implementations, each experiment was conducted during the low-tide peak, in a 1-hour time window, in order to map as much of the site as possible. The photographic material consisted of a full-frame Single Lens Reflex (SLR) CANON 5D Mark II camera with a 36 x 24 mm CMOS sensor installed in the aircraft. We used a wide-angle CANON USM fixed lens of 24 and a 50 mm lens. We paid particular attention to the camera calibration and exposure parameters with a shutter speed of 1/3000s, a camera sensitivity of around 400 ISO, a manual focus set to infinite and a diaphragm aperture maintained at f/8, in order to: avoid motion blur, minimise variability in luminosity, and increase depth of field and optical quality in the border of the image. The flight plan and parameters were designed for our photographic material and selected in a way as to make up for the lack of strongly contrasting morphologies and textures in our field sites. Consequently, we flew close to the ground (< 300 hundred metres) in order to obtain a picture resolution less than or equal to 3.5 cm ground size pixel (GSD) and a scene size corresponding to a 200 x 130 m picture footprint. We chose the parallax parameters using an overlap between pictures of about 85 % end-lap in the lengthwise flight direction and about 50 % side-lap between paths. Considering the scene size and the parallax parameters, we flew at a speed of 100 km/h in order to keep an end-lap ratio with a shooting range of one picture per second. Moreover, we defined numerous parallel flight axes spaced tens of metres. The stereopair alignment using SfM photogrammetry was based on benchmark points in each site. In each implementation, we dropped off several targets of 40 x 40 cm which were accurately georeferenced at a centimetre accuracy using a Real Time Kinematic-Differential Global Positioning System (RTK-DGPS). These target points are named Ground Control Points (GCPs). Furthermore, we sampled, randomly and following specific morphologies, numerous topographic points named Ground Truth Points (GTPs) in order to assess the quality of our DSMs.

The main improvement in photogrammetry and its increasingly widespread use nowadays result from the association of computer vision algorithms with those of traditional photogrammetry. This new paradigm does away with what was hitherto a tedious task wherein the operator had to find homologous points for aerotriangulation. This task is now automatically accomplished using the fast point recognition algorithm called Scale Invariant Feature Transform (SIFT; Lowe, 2004). It allows identification of several thousands of invariant points in each image that are then matched with other images to create a large set of tie points. The SfM photogrammetry workflow was operated using Agisoft Photoscan Professional software.
We describe below the four main steps of the method (fig. 2):

1. Picture quality assessment and masking of mobile objects. First, the picture dataset was imported into Photoscan. Blurred images were filtered and then on each image we masked mobile objects such as aircraft shadow, people or cars, and water surfaces.

2. Picture alignment. This is one of the most important procedures in the SfM protocol. At this stage PhotoScan uses a tracking algorithm to identify, match and monitor the movement of the unique features of the object (Verhoeven, 2011; Javernick et al., 2014; Agisoft, 2015). This algorithm is based on an improved version of the SIFT object recognition system (Lowe, 2004). The software then determines the camera’s intrinsic parameters such as principle point coordinates, skew coefficient and also lens distortion and extrinsic parameters that are rotation and translation parameters necessary for the transformation from 3D object coordinates to 3D camera coordinates. It does so by reconstructing the optimal picture positions, and improves them with a bundle-adjustment algorithm (Robertson and Cipolla, 2009; Verhoeven, 2012; Javernick et al., 2014). SfM is innovative because, regarding scene reconstruction, it does not require a priori 3D picture locations and orientations and also a metric camera, unlike traditional photogrammetry. As a result, sparse point clouds and a set of picture positions in a relative coordinate system are formed. Following this, the first picture alignment must be transformed into an absolute spatial reference. To accomplish this, the sparse cloud model and

![Fig. 2 – SfM Photogrammetry protocol.](image1)

This simple scheme presents our global workflow from field work to the end product and the quality assessment, together with example captions.

![Fig. 2 – Protocole établi pour la photogrammétrie SfM.](image2)

Ce schéma simplifié présente notre méthodologie depuis l’acquisition de terrain jusqu’au produit final et l’évaluation de sa qualité, avec des exemples d’illustrations.
the picture alignment are georeferenced with GCPs in the working
geodetic system of the area. The GCPs are checked on each picture
at infra-pixel scale. The optimization process then adjust the picture
alignment, and allows enhancing the accuracy of GCP positions by
one order of magnitude from 1 decimetre to 1 centimetre.

3. Dense point cloud and mesh model. This stage consists in
building a dense point cloud using the dense picture correlation
algorithm (Furukawa and Ponce, 2010), and then in triangulating a
mesh between the points. Based on the estimated picture positions,
the program calculates depth information from correlation of each
pair of images and then combines all of them into a single dense point
cloud. In our case, flying at an altitude of 300 m and using a GSD of
3.5 cm, we obtained an aLiDAR-equivalent point cloud density with
200 to 300 points per m².

4. Digital surface model and orthophoto. The final stage consists
in projecting the 3D mesh model onto a 2D plane system, thus
generating a gridded raster image named digital surface model
(DSM). DSMs generated by SfM-photogrammetry render visible
all information contained in the original pictures, such as bare
ground but also above-ground elements such as vegetation, roads,
buildings, etc. The DSMs are exported with a resolution close to 2
times the GSD. We chose to interpolate all of our DSM exports with
a resolution of 10 cm for Montjoly beach and 5 cm for the Sinnamary
mudflat and Buëch River channel. We also exported orthophotos at
GSD resolution.

Following this, we assessed the quality of object reshaping. We
based our protocol on a qualitative observation of morphology
reconstruction in each case, and we conducted a quantitative
assessment from the root mean square errors (RMSE) of GCP
locations provided by Photoscan and from the difference between
the DSM and GTPs values, noted ∆h. In the case of a normal
distribution of ∆h, classical statistical indices are used such as the
mean error µ, the standard deviation σ, and the RMSE. However, the
∆h distributions in SfM-photogrammetry are more frequently non-
normal with numerous outliers. Consequently, we also integrated
other estimators less sensitive to outlier data such as the median m,
and the Normalized Median Absolute Deviation (NMAD) that have
been proposed by Höhle and Höhle (2009).

We highlighted also the link between the ground texture and the
Δh error distribution using a ground surface classification from the
orthophotos. We determined by photo-interpretation five classes on
the beach and three on the braided river. The choice of classes was
based on the degree of water saturation and vegetation cover. We
did not carry out a classification of the mudflat surface because the
number of GTPs, 38, is too small to conduct this operation.

Finally, we calculated sediment budgets of Montjoly beach and
the Buëch River. For Montjoly beach, this was carried out through a
comparison of the DSMs produced from the three photogrammetric
surveys between October 2013 and October 2014, and for Buëch by
comparison of a 50 cm ground resolution aLiDAR DSM produced
in January 2011 with a DSM provided by our photogrammetric
survey in March 2014. All the comparisons were based on pixel-to-
pixel elevation subtraction between DSMs using the GIS software
ESRI ArcGIS desktop 10.2 and its extension Spatial Analyst. We
ensured that the compared DSMs were orthogonal to each other
and with the same spatial coverage and ground resolution in order
to avoid misinterpretations of elevation changes. This is why we re-
interpolated the Buëch River photogrammetric DSM from 5 cm to
50 cm in order to compare it with the aLiDAR DSM. The result of
this method is a digital elevation model (DEM) of differences, named
DoD. We also created a layer, including over ground objects and water
surfaces. This layer was used as a mask to keep only ground surfaces
in the volume calculation. The volume change computation was
obtained by multiplying the pixel value of the DoD by its area. The
sediment budget was obtained by comparing volume gains and losses.

The uncertainty regarding the sediment budget is an indispensable
element in assessing whether the calculated volume changes are
significant relative to the vertical accuracy of the DSM. To ascertain
this, we propagated the vertical uncertainty of each DSM over the
DoD using the square root of the sum of squares (usually named sum
in quadrature) of their NMAD values from the entire GTPs dataset.
The resulting error is named EDoD. Then, the error for gains and
losses volumes was obtained by multiplying the pixel areas by the
EDoD. The error for the sediment budget was computed by the sum
in quadrature of errors of gain and loss volumes.

Tab. 1 – DSM density and accuracy for each site derived from Photoscan
and based on the vertical accuracy of the GTPs over bare ground surfaces

<table>
<thead>
<tr>
<th>Flight date</th>
<th>Montjoly beach (08/10/2014)</th>
<th>Sinnamary mudbank (10/10/2014)</th>
<th>Buëch River (14/03/2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point cloud density in points per m²</td>
<td>204</td>
<td>226</td>
<td>375</td>
</tr>
<tr>
<td>GCP accuracy from Photoscan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Easting mean error in cm</td>
<td>0.44</td>
<td>4.34</td>
<td>0.3</td>
</tr>
<tr>
<td>Northing mean error in cm</td>
<td>0.25</td>
<td>3.04</td>
<td>0.37</td>
</tr>
<tr>
<td>Elevation mean error in cm</td>
<td>0.93</td>
<td>2.66</td>
<td>0.52</td>
</tr>
<tr>
<td>RMSE error in cm</td>
<td>1.05</td>
<td>5.93</td>
<td>0.71</td>
</tr>
<tr>
<td>Reprojection mean error in pixel</td>
<td>0.72</td>
<td>0.85</td>
<td>0.41</td>
</tr>
<tr>
<td>GTP vertical accuracy over bare ground</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GTP (nx)</td>
<td>516</td>
<td>38</td>
<td>540</td>
</tr>
<tr>
<td>Mean error (µ) in cm</td>
<td>-2.32</td>
<td>-0.28</td>
<td>5.34</td>
</tr>
<tr>
<td>Standard Deviation (σ) in cm</td>
<td>8.32</td>
<td>4.11</td>
<td>5.27</td>
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<tr>
<td>Root Mean Square Error (RMSE) in cm</td>
<td>8.63</td>
<td>4.06</td>
<td>7.47</td>
</tr>
<tr>
<td>Median (m) in cm</td>
<td>-2.26</td>
<td>-0.27</td>
<td>4.87</td>
</tr>
<tr>
<td>Normalized Median Absolute Deviation (NMAD) in cm</td>
<td>5.81</td>
<td>3.58</td>
<td>3.38</td>
</tr>
</tbody>
</table>
4. Results

4.1. SfM photogrammetry accuracy

The first model quality assessment is provided by the Photoscan software itself and consists in estimating the RMSE of location deviations of the GCPs. In each of the study sites, the results are very good (tab. 1). The estimated easting and northing coordinates of GCPs have infra-centimetre accuracy. The estimated elevation shows centimetre accuracy. The picture average projection error is less than 1 pixel. These indicators provide a good assessment of the internal coherence of the photogrammetric process and of the quality of the alignment process, and, consequently, of the depth reconstruction from which are derived the dense point clouds. These accuracy values seem very promising but may be misleading.

Figure 3 shows examples of the spatial distribution of $\Delta h$ errors from GTPs in each of the study sites. The examples are a focus on the DSMs of the Montjoly lagoon inlet, the riverbed near the gravel trap and over...
of the mudflat. A thousand GTPs were taken on these sites, except for the Sinnamary mudflat where ground topographic operations were very difficult to conduct. The data show numerous values between 0 and 10 cm which illustrate a very accurate reconstruction of features such as the incipient aeolian dunes on the upper beach in Montjoly, the braid bars on the Buëch and the consolidated mudflat surface.

However, we also observe that $\Delta h$ values increase significantly from 10 to 30 cm when the ground surface is saturated in water or under a projected shadow. For these types of surfaces, the reshaping appears as degraded. This can be explained by the homogeneous radiometry of wet, watery, and shadowed surfaces that are not coherent on consecutive pictures. Consequently, such surfaces do not allow the SIFT algorithm to extract invariant SIFT points of good quality.

Figure 4 presents the general distribution of $\Delta h$ for each site as a function of its ground surface classes, plotted in a cumulative histogram. The graphs are presented with a range of 5, then 10 cm, and an outlier limit is defined at the ± 30 cm. We distinguish five classes on Montjoly beach: water-saturated surfaces, wet sand, dry sand, surfaces with sparse and with dense vegetation. On the Buëch, we define three classes: braid bar corresponding to the bare ground and dry active channel surfaces, wet surfaces in proximity to water flow and vegetated surfaces mainly on the river banks. It is worth noting that water surfaces are not taken into account because they have a signal/noise ratio higher than that of other surfaces, but due to the lack of turbidity of the river the photogrammetric model seems to provide consistent results and a possible good estimate of the bathymetry. Considering the low number of GTPs on the Sinnamary mudflat, no classes were defined.

Generally, the $\Delta h$ distributions of the three sites over the bare ground surfaces are centred on their mean error and their median (fig. 4 and tab. 1) with values close to, respectively, -2 and 0 cm, except for the Buëch, where the mean error and the median are close to 5 cm. These latter scores between GTPs and DSM elevation can be explained by the roughness of the gravel braid bar, with median granulometry around 2.5 cm. Indeed, the GTPs are measured at the bottom of the gravels while the DSM renders their topmost surface. The standard deviations can differ significantly due to the number of outliers, with values of 8.32 cm for Montjoly beach, 5.27 cm for the Buëch River, and 4.11 cm for the mudflat (tab. 1). The RMSE values are sensitive to outliers and show a score of 8.63 cm on Montjoly beach and 7.47 on the Buëch River (tab. 1).

The NMAD is more accurate in describing the $\Delta h$ distribution without the influence of outliers. Its shows quite good values of 5.81 cm for Montjoly beach, 3.38 cm for the Buëch River and 3.58 cm for the mudflat. However, there are contrasts in accuracy between wet, vegetated and dry surfaces. Table 2 shows the NMAD values relating to ground surfaces for the Montjoly beach and Buëch River DSMs. Dry surfaces are reconstructed with a high accuracy, with, for instance, NMAD values of 6 cm for the dry sand surfaces on Montjoly beach. The wet surfaces show very high values of NMAD, which correspond to the noisy aspect described previously. The vegetated surfaces display variable statistic values depending on the density and height of vegetation. On Montjoly beach, the vegetated areas are mainly composed of creeping plants, which do not significantly affect the 3D model quality. In contrast with the beach, the vegetated riverbanks of the Buëch are characterised by relatively dense vegetation, which is difficult to classify and that increases artificially the $\Delta h$ values and statistic scores. Moreover, the steep slopes of the riverbanks show higher errors but no dedicated statistical study has been carried out on this parameter. These results show that SM photogrammetry is very efficient on poorly contrasted morphologies.

The $\Delta h$ histograms (fig. 4) also show that outliers are concentrated on wet surfaces. Water present on the surface thus appears as the main source of errors in SM photogrammetry. Despite this limitation, the accuracy of morphological reconstruction is very good, including on poorly contrasted and flat terrain. The high quality of these results...
is explained by the fine resolution of the pictures, and by the good quality of the optical lens and sensor. These accurate and well-tuned acquisition parameters allow us to generate some texture on homogeneous surfaces.

4.2. 3D morphological reconstructions and sediment dynamics

SfM photogrammetry generates orthophotos with a very high resolution, in our cases around 3 cm per pixel. A DSM with very high resolution and accuracy can replace traditional topographic monitoring with RTK-DGPS or a total station. Indeed, Figure 5 shows clearly the quality of topographic rendering and of the geomorphic shapes generated. The DSMs generated in the course of the experiments have a resolution of 10 cm per pixel for Montjoly beach and 5 cm for the Buëch River and the Sinnamary mudflat, and yield valuable information on both aspects of morphology and landform dynamics. The DSMs cover the entire beach of Montjoly, including the surf and intertidal zone, and that of Sinnamary a small part of the consolidated mudflat deposits. The experiments on Montjoly beach coincided with a phase of strong erosion just prior to the arrival of a mud bank from the east that generated strong wave dissipation and muting of beach processes as described in the 4-phase model of Anthony and Dolique (2004). Overall, all the DSMs image very well the morphologies of these sites. Regarding Montjoly beach and the Buëch River, we have chosen to present one DSM of each site, respectively, the October 2014 DSM for Montjoly beach and the March 2014 DSM for Montjoly beach.

SfM photogrammetry in this type of environment, highlighting with the accurate and well-tuned acquisition parameters allows us to generate some texture on homogeneous surfaces.

<table>
<thead>
<tr>
<th>Montjoly beach</th>
<th>GTP</th>
<th>Mean error (cm)</th>
<th>Median (cm)</th>
<th>Standard deviation (cm)</th>
<th>RMSE (cm)</th>
<th>NMAD (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-saturated sand</td>
<td>125</td>
<td>10.58</td>
<td>9.8</td>
<td>24.77</td>
<td>26.84</td>
<td>22.46</td>
</tr>
<tr>
<td>Wet sand</td>
<td>136</td>
<td>6.42</td>
<td>6.52</td>
<td>12.25</td>
<td>13.79</td>
<td>15.32</td>
</tr>
<tr>
<td>Dry sand</td>
<td>516</td>
<td>-2.32</td>
<td>-2.26</td>
<td>8.32</td>
<td>8.63</td>
<td>5.81</td>
</tr>
<tr>
<td>Dry sand with sparse vegetation</td>
<td>293</td>
<td>-0.86</td>
<td>-1.57</td>
<td>9.14</td>
<td>9.18</td>
<td>6.39</td>
</tr>
<tr>
<td>Dry sand with dense vegetation</td>
<td>20</td>
<td>0.93</td>
<td>-2.07</td>
<td>9.80</td>
<td>9.60</td>
<td>10.73</td>
</tr>
<tr>
<td>All classes</td>
<td>1090</td>
<td>0.66</td>
<td>-1.79</td>
<td>12.85</td>
<td>12.87</td>
<td>7.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Buëch River</th>
<th>GTP</th>
<th>Mean error (cm)</th>
<th>Median (cm)</th>
<th>Standard deviation (cm)</th>
<th>RMSE (cm)</th>
<th>NMAD (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braid bar</td>
<td>540</td>
<td>5.3</td>
<td>4.87</td>
<td>5.27</td>
<td>7.47</td>
<td>3.38</td>
</tr>
<tr>
<td>Wet surface</td>
<td>211</td>
<td>6.61</td>
<td>6.59</td>
<td>7.82</td>
<td>10.23</td>
<td>6.69</td>
</tr>
<tr>
<td>Vegetation</td>
<td>147</td>
<td>10.79</td>
<td>9.58</td>
<td>12.95</td>
<td>16.82</td>
<td>8.55</td>
</tr>
<tr>
<td>All classes</td>
<td>898</td>
<td>6.51</td>
<td>5.48</td>
<td>7.89</td>
<td>10.22</td>
<td>5.01</td>
</tr>
</tbody>
</table>

All of these features, including the most poorly contrasted ones such as a mild beach scarp, are defined with a realistic shape. In the intertidal and surf zones, however, the morphology is less clear as one goes from the upper beach towards the lower beach due to the predominance of water-saturated surfaces in these zones. We observed this type of quality deterioration on each DSM of Montjoly beach.

The technique has also been useful in monitoring the sediment dynamics involved in the rotation of Montjoly beach. We clearly observe the important longshore transport from the northern to the southern sector of the beach (fig. 6A), highlighting the end of one transition phase in the 4-phase morphodynamic model of Anthony and Dolique (2004). The volumetric differential shows large sediment losses of 75,460 (± 14,800) m³ in the north corresponding to a beach retreat of 25 m, and deposition of 20,000 (± 14,950) m³ in the south over the period October 2013 – October 2014. A comparison of the October 2013 and March 2014 DSMs illustrates the rotation process initiated by an approaching mud bank which induces wave diffraction offshore. Unfortunately, the October 2013 DSM presents a data gap close to southern headland due to a lack of picture coverage during the survey. Consequently, the comparison between the October 2013 and March 2014 DSMs conveys only partial information about the depositional dynamics in sector 6. Between March and October 2014, the beach appears more stable with the termination of the deposition phase in the southern part and minor deposition along the rest of the beach. We have also calculated a preliminary estimate of the volume error involved in the sediment budget calculation. However, this volume error is probably over-estimated, because our calculation propagates the error, EDoD, over the entire surface of the DoD without taking into account the Δh variability between dry and wet or vegetated surfaces. Consequently, the volume error in this sediment budget calculation is maximised. Despite this, the calculated sediment budgets are realistic and the beach behavioural pattern corresponds to the beginning of the “bank” phase and the complete welding of mud onto the beach, thus resulting in total dissipation of offshore wave energy.

The mudflat experiment has also enabled successful testing of SfM photogrammetry in this type of environment, highlighting with the accurate and well-tuned acquisition parameters allows us to generate some texture on homogeneous surfaces.
Fig. 5 – Examples of DSM landform reconstructions.

(A) & (B) Focus on Montjoly lagoon inlet from the October 2014 DSM and orthophoto. Various features such as the lagoon’s ebb delta, an erosion scarp, a bulldozer excavation imprint and mildly developed barkhans, are clearly distinguished. (C) & (D) Overview of the mudflat experimentation site near the Sinnamary river estuary from the October 2014 DSM and orthophoto. Numerous microforms are clearly visible from the DSM such as pits and drainage channel networks. (E) & (F) Focus on a narrow section of the Buëch channel from the March 2014 DSM and orthophoto. The DSM shows a good reconstruction of braided channel features such as the shape of braid bars, various incisions and a log jam with its bedload accumulation.
Fig. 6 – Example of SfM photogrammetry applications.

(A) Montjoly beach volume changes from comparison of DSMs for October 2013 and October 2014. The beach is split into six alongshore sectors evincing variable morphodynamic behaviour: sector 1 is in the most protected part of the beach with rock outcrops in the lower intertidal zone. Sector 2 is the most exposed part of the beach when rotation, involving sand transfer to the southeast, sets in. Sector 3 covers the Montjoly lagoon inlet, a dynamic zone characterised by ebb and flood tidal flows. Sectors 4 and 5 highlight the gradient in beach erosion from the northwest to the southeast, the latter marking the transition to sector 6, the down-drift accumulation zone in the rotation process. (B) Water level above mudflat from pressure sensor measurements and DSM elevation during neap (B1) and spring (B2) tides. This implementation provided an estimation of the water level range required for mangrove colonization which is lower than 25 cm during neap tides. (C) Buëch bedload and channel geometry changes from comparison of a 2011 LiDAR DSM and the 2014 photogrammetric DSM. The river bed displays numerous incisions of braided bars over the study period with channel geometry adjustments expressed by bank erosion and braided bar formation in wide sections. Filling appears to prevail close to the gravel trap.
biofilms created by benthic microalgae and cyanophyceae at the sediment surface, bioturbation by macrobenthic fauna (pits, burrows) and from roots (pneumatophora, rhizophora), and mangrove colonization. Figure 6B shows the water elevation during spring and neap tide from field pressure sensor measurements, and enables us to determine that mangrove colonization of the mudflat can occur with a minimum water level of 25 cm. Mudflat surface consolidation also appears during neap tides, when flooding depths do not exceed 1 m during high tide. Nevertheless, due to technical problems that resulted in non-optimal image acquisition during the flight that, the reconstruction of the morphology of the mudflat (fig. 5C-D) was operated from a dense point cloud of 11 million points, which corresponds to a density of 226 points per m². The DSM clearly highlights features on the consolidated mud surface such as drainage channels and numerous small water-filled pits. On this DSM, we also distinguish the gradual slope increase from fresh mud to the mangrove forest that colonises the highest part of the mudflat. In the southeastern sector, the features are still distinguishable but with artefacts when there is not enough side-lap between pictures. Several artefacts appear also on the water-filled pits. This demonstrates that water surfaces are not suitable for photogrammetry and misinterpretations of elevation can be generated. The composition, topography and structure of microhabitats in such landforms (channels, pits and vegetation) are a valuable tool for identifying organism-sediment relationships and for providing an accurate cartography of biodiversity distribution. Such reconstructions at a higher resolution should also provide an accurate definition of the sediment surface in relation with biological sediment reworking. Characterization of the surficial sediment at a finer scale should also be a useful tool in accurately quantifying biogeochemical exchanges (net and diffusive fluxes) at the sediment-air or sediment-water interfaces.

Regarding the Buëch River experiment, the model provides elevation information for all types of surfaces, surprisingly including water-filled channels due to very clear water as said before. The active channel morphology was reconstructed from a dense point cloud of 500 million points for the 3.2 km long reach upstream of the gravel trap structure. This corresponds to a density of about 350 points per m². The DSMs and the orthophotos were generated with a resolution of 5 cm per pixel (fig. 5E-F). Qualitatively, river features such as braid bars, log jams and their associated bedload accumulations, various incision forms and the vegetated riverbanks, are very well reconstructed. The shapes of decimetric-scale incision features are also respected. We also observed also, as in the other SM experiments, that wet, water-saturated surfaces and surfaces over which a shadow is cast are not well reconstructed and the morphology less clear than on dry surfaces.

We also compared the January 2011 DSM from the aerial LiDAR survey with that generated by our March 2014 SM photogrammetry survey (fig. 6C), and obtained an accurate estimation of the bedload changes during the January 2011 – March 2014 period. The water-filled channels, which do not appear on the LiDAR DEM, were not taken into account and we compared only dry surfaces such as braid bars and riverbanks without or with sparse vegetation. The comparison provided an estimated volume balance over an area of 0.7 km², with deposition of 16,800 (± 8,000) m³ and erosion of 48,650 (± 11,770) m³, indicating a bedload shortage of 31,850 (± 14,230) m³ over the period. The volume error calculation over this sediment budget is affected by the same limitations as those of the Montjoly beach study. The active channel showed overall lowering, with infill resulting from the formation of a braid bar close to the gravel trap. Large riverbank and braid bar erosion were also observed along narrow sections where sediment mobilization is impeded. Finally, the comparison provided accurate monitoring of channel interlacing and lateral migration patterns in the braided sections (fig. 6C).

5. Conclusion

SfM photogrammetry constitutes a good-compromise method for morphometric surveys of dynamic features such as beaches, mudflats and braided rivers. We applied the technique to three sites and reconstructed with accuracy and high resolution the topography of dynamic geomorphic features. The generated data also yielded useful information on morphodynamic and sediment transport aspects. The main advantage of this technique is its reproducibility. We generated very-high resolution DSMs and orthophotos of the surveyed sites. We also show that DSM accuracy, generally less than 10 cm, decreases significantly to 30 cm in the presence of water or water-saturated surfaces which constitute the main limitations of SM photogrammetric monitoring of coastal and fluvial features. We proposed a method to assess the propagation of the vertical uncertainty of each DSM over the DoD and thus to assess volume uncertainty over sediment budget. However, this uncertainty tends to be over-estimated. Several enhancements can be implemented to attain a very accurate assessment of the volume error of the sediment budget. These include for instance, taking into account the spatial variability of the vertical uncertainty depending on the ground surface, and its propagation over the DoD.

Low-cost and user-friendly SfM photogrammetry offers interesting new perspectives in geomorphology requiring high-resolution topographic data. The technique combines the reproducibility of traditional topographic surveys using RTK-DGPS or a total station and the high density and accuracy of LiDAR, but at much lower cost than the latter. SfM photogrammetry is more than a promising tool for fast and accurate morphometric and morphodynamic surveys in numerous fields of geomorphology.

Acknowledgments

We acknowledge support from CEREGE UM 34 for funding the October 2013 experiment. We thank the CNRS Mission Interdisciplinaire et le Pépinière Interdisciplinaire de Guyane GUIASANDBEACH project for funding in 2014. Further support was provided by the Belmont Forum Project « BF-Deltas: Catalyzing Action Towards Sustainability of Deltaic Systems with an Integrated Modeling Framework for Risk Assessment ». Finally, we appreciate the operational support from the coastal team of the CNRS French Guiana office. We acknowledge also support from DDT 04 for funding the Buëch River experiments, and SMIGIBA and EDF for fruitful collaboration on this project. Part of this work was supported by the French National Agency under the « young researcher » programme (BIOMANGO project: ANR-12-JSV7-0012-01). Co-funding by the ISIS programme managed by Astrum Geo Information Service under the supervision of the Centre National d’Études Spatiales (CNES) is also acknowledged. We thank the two anonymous reviewers for their constructive remarks and corrections.

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DOI: 10.1144/SP388.8


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La compréhension des objets et des processus géomorphologiques dans des environnements dynamiques peut être grandement améliorée par la reconstitution haute résolution de la morphologie de l'objet d'étude. Actuellement, plusieurs solutions permettent de reconstruire la forme d'un objet en haute résolution comme le Light Detection and Ranging aéroporté (aLiDAR), le Scanner Laser Terrestre (SLT) et la photogrammétrie Structure from Motion (SfM). Ces différentes techniques présentent cependant des contraintes de couverture spatiale, de densité d'information, de précision, de coûts, et de reproductibilité, les rendant potentiellement difficilement applicables à l'étude des changements morphologiques rapides affectant les objets géomorphologiques (Passalacqua et al., 2015).

La technique de photogrammétrie SfM connait actuellement un fort engouement dans les domaines de la métrologie et des géosciences. En effet, son application est (1) peu coûteuse au regard des techniques de laseragéométrie citées précédemment, (2) sa mise en œuvre est accessible à des non-spécialistes, (3) son rayon de déploiement varie de quelques mètres à plusieurs kilomètres selon la plateforme utilisée pour le suivi photographique (hélicoptères, Ultra Léger Motorisés-ULM, drones, cerf-volants, perche et prise de vue à la main ; Bryson et al., 2013 ; Javernick et al., 2014 ; Tonkin et al., 2014 ; Gonçalves et Henriques, 2015 ; Smith et Vericat, 2015 ; Brunier et al., 2016) et (4) elle permet des rendus denses et précis de la morphologie de l'objet.

Cette étude utilise de manière originale la photogrammétrie SfM aéroportée pour constituer des modèles numériques de surface (MNS) 3D très haute résolution de trois objets géomorphologiques dans des milieux dynamiques. Nous avons par ailleurs cherché à quantifier précisément l'évolution morphologique de deux de nos sites. Notre étude porte en premier lieu sur des reconstructions multiples de la morphologie de la plage de baie de Montjoly près de Cayenne en Guyane. La photogrammétrie SfM nous a permis de suivre le processus de rotation rapide de cette plage, induit par le transit côtier de bancs de vases (Anthony et al., 2010, 2014) sur la période octobre 2013 – octobre 2014. Notre travail s'oriente ensuite vers une reconstitution haute résolution de la surface d'une vasière intertidale appartenant à l'un des bancs de vase transitant sur la côte guyanaise, au niveau de l'estuaire du fleuve Sinnamary. Enfin, nous avons suivi l'évolution d'une rivière en tresse, le Buëch, dans les Alpes du Sud, dont les flux de sédiments sont estimés précisément depuis 2011 afin de comprendre les interactions entre cycle naturel et impact des aménagements anthropiques sur l'érosion et la sédimentation.

Notre méthode repose sur un protocole de terrain léger et souple incluant en premier lieu des prises de vues verticales à basse altitude depuis un ULM (altitude 280 m ; appareil reflex plein format ; 2,5 à 4 cm/pixel sol). Au sol, nous déployons et levons au GPS différentiel cinématique (RTK), plusieurs cibles sur l'objet qui servent de Points de contrôle au Sol (PCS), pour géoréférencer le modèle 3D. Nous mesurons ensuite de manière aléatoire des points topographiques, appelés « Points de Vérité Terrain (PVT) », afin d'évaluer la qualité du MNS de sortie. Nous opérons la production des modèles 3D et des orthophotographies à l'aide du logiciel Photoscan Professional d'Agisoft®. L'évaluation de la qualité des MNS est basée sur les erreurs de positionnement des PCS, puis sur l'étude statistique des différences d'altitude entre les PVT et le MNS, notées Δh. Nous étudions la relation entre la distribution spatiale des erreurs Δh et la nature de la surface à l'aide d'une classification de cette dernière par photo-interprétation sur l'hélico-image. Ensuite, nous calculons des bilans sédimentaires sur les sites de la plage de Montjoly et du chenal du Buëch. Notre méthode consiste à réaliser des modèles numériques des différences d'altitude (MNDAs) entre des MNS issus de la photogrammétrie (plage de Montjoly) ou issus de la photogrammétrie et du aLiDAR (Buëch). Nous retenons l'écart absolu normalisé par rapport à la médiane EANM comme incertitude verticale sur les MNS. La quantification de l'erreur sur les bilans sédimentaires est basée sur la propagation au MNS des valeurs d'incertitude de chaque MNS.

L'ensemble des MNS réalisés sur les différents environnements affiche une résolution de 5 (vasière et rivières) à 10 cm (plages) par pixel. Les orthophotographies sont produites avec une résolution de 3 cm par pixel. Ces MNS montrent une image fine et cohérente de la morphologie des objets observés comme des formes éoliennes sur le haut de plage, des microfailles d'érosion en pied de plage, les réseaux de chenaux tidaux sur la vasière ou encore la géométrie d'un chenal en tresse avec ses bancs de galets et ses formes d'incision. Une dégradation de la cohérence des formes sur les MNS apparaît néanmoins lors de la reconstitution de surfaces humides ou s'atténuant en eau. La précision des MNS affiche des valeurs infra-centimétriques dans les composantes horizontales et centimétriques dans la composante verticale pour les PCS. La distribution statistique des valeurs de Δh pour les sols nos montre une excellente précision, tous sites confondus, avec des valeurs de moyennes et de médianes autour de 0 cm et des indices de dispersion (écart-type, erreur quadratique moyenne (EQM) et écart absolu normalisé à la médiane (EANM)) entre 5 et 10 cm. Nous remarquons par ailleurs que l'influence de la végétation basse à l'échelle de ces modèles joue un rôle de sursol variable selon sa nature et sa densité. Des erreurs non-linéaires persistent sur les modèles où les surfaces humides ou en eaux sont reconstituées avec une imprécision de 20 à 30 cm. La nature de ces surfaces trop peu cohérentes, en mouvement ou sujettes à la réflexion de la lumière, constitue la principale limitation de la technique.

Sur la plage de Montjoly, les deux MNDAs couvrant les périodes octobre 2013 – mars 2014 et mars 2014 – octobre 2014 soulignent clairement le phénomène de rotation et de balancement du stock sédimentaire sous influence du transit vers l'ouest d'un banc de vase. Nous avons quantifié une forte érosion de 75 460 (± 14 800) m³ sur la moitié Nord de cette plage et un transfert de 20 000 (± 14 950) m³ sur la pointe Sud. Il s'agit de la première quantification du transit sédimentaire pendant la première phase de rotation de cette plage lorsque le banc en provenance de l'Est inverse le sens de la dérive littorale vers le Sud (Anthony et Dolique, 2004).

Le MNS de la vasière sur le banc de vase de Sinnamary, réalisé en octobre 2014, permet, de manière inédite, de quantifier avec précision la morphologie de ce type de site comme le réseau de chenaux de marée et les faciès défrançonnés en vasques des réseaux bioturbés de la...
vasière. De plus, ce MNS permet de mettre en évidence les relations entre les niveaux de consolidation des dépôts de vase, l’installation de la mangrove et les niveaux d’eau mesurés lors de cycles de marée de vives et de mortes eaux.

Enfin, le MNDA sur le Buëch a permis de mettre en évidence les changements morphologiques d’une partie de ce cours d’eau en tresse dans un contexte de forte pression anthropique avec la mise en place d’un piège à gravier à l’aval du site d’étude en 2010. Nous avons quantifié une perte de 48 650 (± 11 770) m³ contre 16 800 (± 8 000) m³ de dépôts, soit un bilan sédimentaire négatif sur la période étudiée. Ce bilan est reflété par des réajustements de la géométrie du chenal comme l’érosion de berge et la tendance à l’incision. Les zones en accumulation correspondent à la migration de bancs de graviers.

La technique de photogrammétrie SfM offre de nouvelles perspectives en Géomorphologie grâce à son faible coût, à la précision des MNS produits et à sa facilité de mise en œuvre via un grand choix de plateformes comme les ULM ou les drones.